Working Paper Series

MIT Center for Energy and Environmental Policy Research

Sustainable Hydrogen Fuels versus Fossil Fuels for Trucking, Shipping and Aviation: A Dynamic Cost Model

Jonas Martin, Anne Neumann, and Anders Ødegård

JULY 2022

CEEPR WP 2022-010

Working Paper Series.

SUSTAINABLE HYDROGEN FUELS VERSUS FOSSIL FUELS FOR TRUCKING, SHIPPING AND AVIATION: A DYNAMIC COST MODEL

Jonas Martin*[1], Anne Neumann[1], Anders Ødegård[2]

[1]Norwegian University of Science and Technology, Department of Industrial Economics and Technology Management, Trondheim, Norway | jonas.martin@ntnu.no, anne.neumann@ntnu.no

[2]SINTEF, Department of Sustainable Energy Technology, Trondheim, Norway | anders.odegard@sintef.no

---

Potential decarbonization of the global trucking, shipping and aviation sectors by 2050 could be achieved by replacing fossil fuels with sustainable hydrogen fuels (SHF). We develop a dynamic cost model and apply it to Norway, considered an early adopter of sustainable transport. Modelling the value chains from electricity and fuel production to fuel consumption for long-haul trucking, short-sea shipping and short-haul aviation allows us to compare the changes in competition from SHF versus fossil fuel use. Outlining the total costs of ownership indicates that the optimal SHF choices are hydrogen for long-haul trucking, ammonia for short-sea shipping, and hydrocarbon eFuel for short-haul aviation. Although the optimal SHF choices do not change the cost rankings across the freight transport modes, short-sea shipping has the strongest transport cost sensitivity (+232%, 2020; +41%, 2050), followed by short-haul aviation (+138%, 2020; +36%, 2050) and long-haul trucking (+66%, 2020; +8%, 2050).

Achieving net zero emissions by 2050[1,2] represents a significant challenge for the global trucking[3–6], shipping[4,7–10] and aviation[4,11–13] sectors. Unlike the continuous improvements in battery storage technology for passenger and light-duty vehicles[4,14], only fossil fuels meet the considerable technical and economic requirements[4,9,11,14–16] of most truck, ship and plane traffic. Hence with the regulatory banishment[2] of greenhouse gas emissions (GHG), there is widespread interest in using sustainable hydrogen fuels (SHF) - not only due to more efficient land use and scalability compared to biofuels[4,14]. Produced from renewable energy sources, water, and optionally carbon dioxide[14] or nitrogen[17] captured from the atmosphere, the respective fuels are hydrogen[18] (eH, eHydrogen), hydrocarbon fuels[14,15] (eF, eFuel) and ammonia[17] (eA, eAmmonia); the e stands for renewable, electricity-based fuels. eFuel can be used in existing combustion engines, whereas eH and eA depend on electrochemical conversion in fuel cells[16,19] or adjustments[4] in combustion engines and fuel tanks. The most promising technical fuel pathways are eH and eF for long-haul trucking[3–5], eH, eF and eA for short-sea shipping[4,7–10,20] and eH and eF for short-haul aviation[4,11–13] as shown in Figure 1.

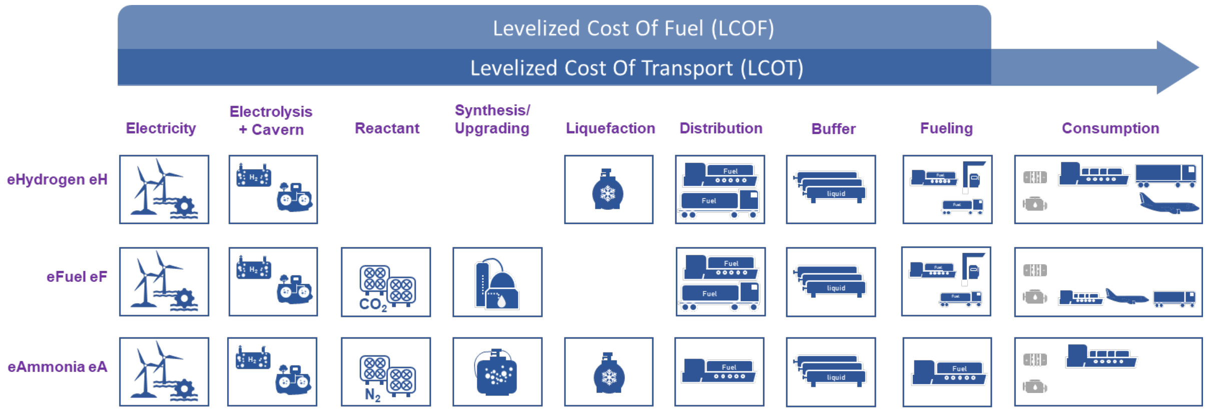

Figure 1 Three value chains of fuel supply and consumption. Adjusting the dynamic cost model to account for different sources of sustainable electricity generation, fuel production and distribution obtains the levelized cost of fuel (LCOF) and the levelized cost of transport (LCOT) for the trucking, shipping and aviation. (Source: own illustration)

SHF use, however, is cost-intensive. Previous studies investigate the value chains illustrated in Figure 1 in regard to the eH[18,21–23], eA[17,23,24] and eF[14,15,23,25] costs, costs of decarbonizing trucking[3,6,26–28], shipping[7–9,20] and aviation[11–13], and the technical usability of alternative fuels[4]. While most transport studies rely on various sources of external fuel costs[3,4,7,9,11,13,20,26,27] or focus on one mode[3,6–9,11–13,20,26,27], a reliable cost comparability of fuels and transport modes only occurs with uniform assumptions of the value chains' horizontal and vertical dimensions.

To understand the economic changes while decarbonizing long-haul trucking, short-sea shipping and short-haul aviation, this paper describes a dynamic cost model. Its 140 parameters can be tailored to local conditions with reference to renewable energy production (electricity and SHF), distribution (tank ship, tank truck, storage, fuel station) and the use in the trucking, shipping and aviation sectors. The results show that while each mode has optimal SHF choices, the market competitiveness of sustainable transport cannot be achieved by 2050. Compared to current fossil-based transport without government intervention, shipping has the strongest transport cost sensitivity (+232%, 2020; +41%, 2050), followed by aviation (+138%, 2020; +36%, 2050) and trucking (+66%, 2020; +8%, 2050). The alternative fuels do not change the cost rankings of transport modes. The type of renewable electricity generation, however, will impact early decarbonization.

Model framework

We can accommodate the dynamic cost model to local conditions with reference to energy production (electricity and SHF), fuel distribution (tank ship, tank truck, storage, fuel station) and transport needs (trucking, shipping, aviation). We apply technology and cost data for 140 parameters. We assume the cost of all production components at industrial scale and increasing market diffusion, following the literature[14–16,18,29]. Hence, strong scaling and learning effects for all components shape the collected cost curves. We apply our model to Norway, which depends on all three transport modes due to its long coastline, rough terrain and dispersed population[32]. Norway also has excellent renewable energy potential. We neglect the option of fuel import from other countries[15,17,23,25] with high wind and sun potential and focus on domestic production.

Based on equations (1) and (2) below, we calculate the levelized cost of electricity[30,31] (LCOeEl) for offshore wind, onshore wind and hydropower (step 1), fuel options (LCOF) (step 2) and cross-mode heavy-duty transport (LCOT) (step 3), with the *LCOX* levelized cost of an arbitrary process X (for example, wind power, electrolysis, transport), $Capex_x$ capital expenditures of *X*, *UCRF* universal capital recovery factor, $Opex_{x,fix}$ fixed operational expenditures of *X* per year, Q_x annual outcome quantity of *X* and $Opex_{x,var}$ variable operational expenditures of *X* per outcome unit. We set the weighted average cost of capital (WACC) to 6 % over *N* as the specific lifetime of *X*.

$$LCOX = \frac{Capex_x * UCRF + Opex_{x,fix}}{Q_x} + Opex_{x,var} \tag{1}$$

$$UCRF = \frac{WACC * (1+WACC)^N}{(1+WACC)^N - 1} \tag{2}$$

Several technologies face high uncertainties in our cost estimations, so we implement a range of cost values to investigate the model's sensitivity in a best- and worst-case scenario and a base-case scenario. See Figures **2–7** in the sections on levelized costs. We analyse the electricity, fuel and transport costs in five-year increments from 2020 to 2050. We do not include taxes and subsidies for fossil and sustainable alternatives. We assume that eH and eA are used in fuel cells and that fossil fuel (fF, fFuel) and eF are used in mode-specific internal combustion engines. We consider costs of necessary replacements of components, such as fuel cells, over the vehicle's lifetime by assuming proportionally higher CAPEX. We compare the final results for fuels in € per kWh and for transport in € per tonne-kilometre. Results of transport cost based on the energy source "onshore wind" are shown in the main text. Results based on offshore wind and hydro power are in the appendix. See Table **1** below and the supplementary information (SI) for the details.

	2020	2035	2050
Wind offshore; onshore Full load hours	€3,200 kW_{el}^{-1}; €1,500 kW_{el}^{-1} h4,400 a^{-1}; h3,200 a^{-1}	€2,000 kW_{el}^{-1}; €1,030 kW_{el}^{-1} h4,400 a^{-1}; h3,200 a^{-1}	€1,650 kW_{el}^{-1}; €950 kW_{el}^{-1} h4,400 a^{-1}; h3,200 a^{-1}
Hydropower Full load hours	€2,350 kW_{el}^{-1} h7,000 a^{-1}		
Electrolysis	€1,100 kW_{el}^{-1}	€525 kW_{el}^{-1}	€330 kW_{el}^{-1}
eH liquefaction [electricity demand]	€2,300 kW_{H2}^{-1} [kWh_{el} 0.36kWh_{H2}]	€1,255 kW_{H2}^{-1} [kWh_{el} 0.22kWh_{H2}]	€700 kW_{H2}^{-1} [kWh_{el} 0.21kWh_{H2}]
eFuel synthesis	€800 kW_{fuel}^{-1}	€525 kW_{fuel}^{-1}	€400 kW_{fuel}^{-1}
CO_2 costs	€460 t^{-1}	€135 t^{-1}	€80 t^{-1}
eAmmonia synthesis	€995 kW_{fuel}^{-1}		
Fuel station ((fF/eF; eH)	€2M; €6M	€2M; €4M	€2M; €3M
Truck unit (fF/eF; eH) [fuel demand]	€110k; €350k [kWh_{LHV}3.2 km^{-1}; kWh_{LHV}2.98 km^{-1}]	€110k; €150k [kWh_{LHV}3.2 km^{-1}; kWh_{LHV}2.75 km^{-1}]	€110k; €140k [kWh_{LHV}3.2 km^{-1}; kWh_{LHV} 2.69 km^{-1}]
Ship (fF/eF; eA; eH) [fuel demand]	€50M; -; - [kWh_{LHV}498 km^{-1}; -; -]	€50M; €100M; €100M [kWh_{LHV}498 km^{-1}; kWh_{LHV}411 km^{-1}; kWh_{LHV}411 km^{-1}]	€50M; €60M; €65M [kWh_{LHV}498 km^{-1}; kWh_{LHV}400 km^{-1}; kWh_{LHV}400 km^{-1}]
Aircraft (fF/eF; eH) [fuel demand]	€50M; - [kWh_{LHV}38.8 km^{-1}; -]	€50M; €125M [kWh_{LHV}38.8 km^{-1}; kWh_{LHV}38.8 km^{-1}]	€50M; €65M [kWh_{LHV}38.8 km^{-1}; kWh_{LHV}38.8 km^{-1}]

Table 1 Main input variables. Base case scenario, see SI for the details.

Levelized cost of electricity

We calculate the levelized cost of electricity for Norway's locally available renewable energy sources. We neglect solar power because it is not a significant source of electricity generation in Norway. For offshore wind, we use data from 'Sørlige Nordsjø II' in the North Sea with full load hours of 4,400 h/a[32], and consider a fee[25] for grid connection to the mainland. For onshore wind, we use a representative location on the Norwegian coastline with full load hours of 3,200 h/a[33]. For large hydropower, we use data from "Aura" in Mid-Norway assuming full load hours of 7,000 h/a[25,34] and do not consider a further potential in cost decrease[25,35]. See the levelized cost (LCOeEl) in Figure **2A.**

Levelized cost of eHydrogen

Sustainable hydrogen is produced in electrolysers using renewable electricity to split water into hydrogen and oxygen. Burning the hydrogen in fuel cells releases most of the energy input as electricity. Thus, the hydrogen acts as an energy carrier with a high gravimetric (33.33 kWh_{LHV}/kg[4]) but low volumetric energy density (2.359

kWh_{LHV}/l_{liquid}[4]). Polymer electrolyte membrane and alkaline-based electrolyser types are commercially available. We assume an average value[15] for both types. The electrolyser only works when electricity is being produced and thus it has the same full load hours as the chosen electricity source. Ensuring a consistent operation of subsequent process steps the hydrogen produced is buffered and stored in underground lined rock caverns[36–38].

For the distribution of eH, the gas is liquified at -252.8 °C using a cryopump system[37]. The energy-intensive process requires stable, renewable electricity[37] supplied by the Norwegian grid. For all modes, tank ships[15,23] transport the first part of the fuel distribution (~500 km) to ports and seaside airports along the Norwegian coast. For the trucking mode, tank trucks[15,22] transport the second part to the fuel stations inland (~150 km). We include a liquid hydrogen buffer to decouple supply and demand. The eHydrogen deliveries are handed over to the local refueling infrastructure. See the levelized cost (LCOeH) in Figure **2B**.

Levelized cost of eAmmonia

The shipping sector is also interested in eAmmonia[9] due to its favourable liquid handling under -33°C[4], and lower gravimetric (5,28 kWh_{LHV}/kg[19]) but higher volumetric (3.19 kWh_{LHV}/l_{liquid}[19]) energy density. The feedstock hydrogen is stored in underground lined rock caverns. To produce eAmmonia, a second reactant nitrogen is captured from the atmosphere. The Haber-Bosch process transforms hydrogen and nitrogen to ammonia with subsequent liquefaction, a mature, common technology used in fertiliser production[17]. The energy-intensive process requires stable, renewable electricity[23] supplied by the Norwegian grid. We include a liquid ammonia buffer to decouple supply and demand. As a maritime fuel, only tank ships[23] transport eA to ports (~500 km) along the Norwegian coast. The eAmmonia deliveries are ready to be handed over to the end-use ship. See the levelized cost (LCOeA) in Figure **2C**.

Levelized cost of eFuel

In eFuel production we do not distinguish between hydrocarbon end products (diesel, heavy fuel oil, jet fuel)[14]. We neglect the fuel alternative methane because its possible leakage contributes to global warming[4]. Synthetic hydrocarbons are near-identical copies of fossil fuels for use as blending or substitution in modern internal combustion engines[4,15]. Their molecular structure of carbon and hydrogen offers a very high gravimetric (~11.5 kWh_{LHV}/kg[4]) and volumetric (~10 kWh_{LHV}/l_{liquid}[4]) energy density similar to their fossil counterparts. The feedstock hydrogen is stored in underground lined rock caverns. To produce eFuel, a second reactant carbon is captured from the atmosphere[15,39]. We assume a CO_2 direct air capture plant based on low-temperature solid sorbent technology[40] that filters CO_2 from the ambient air. The hydrocarbon synthesis transforms carbon and hydrogen to synthetic crude oil, followed by upgrading to the desired end product[15,23,25]. The energy-intensive process requires stable, renewable electricity[23] supplied by the Norwegian grid. The distribution of eF follows the same procedure as for eH, but benefits from easy handling and storage without cooling or pressurizing. We include an eF buffer to decouple supply and demand. The eFuel deliveries are handed over to the local refueling infrastructure. See the levelized cost (LCOeF) in Figure **2D**.

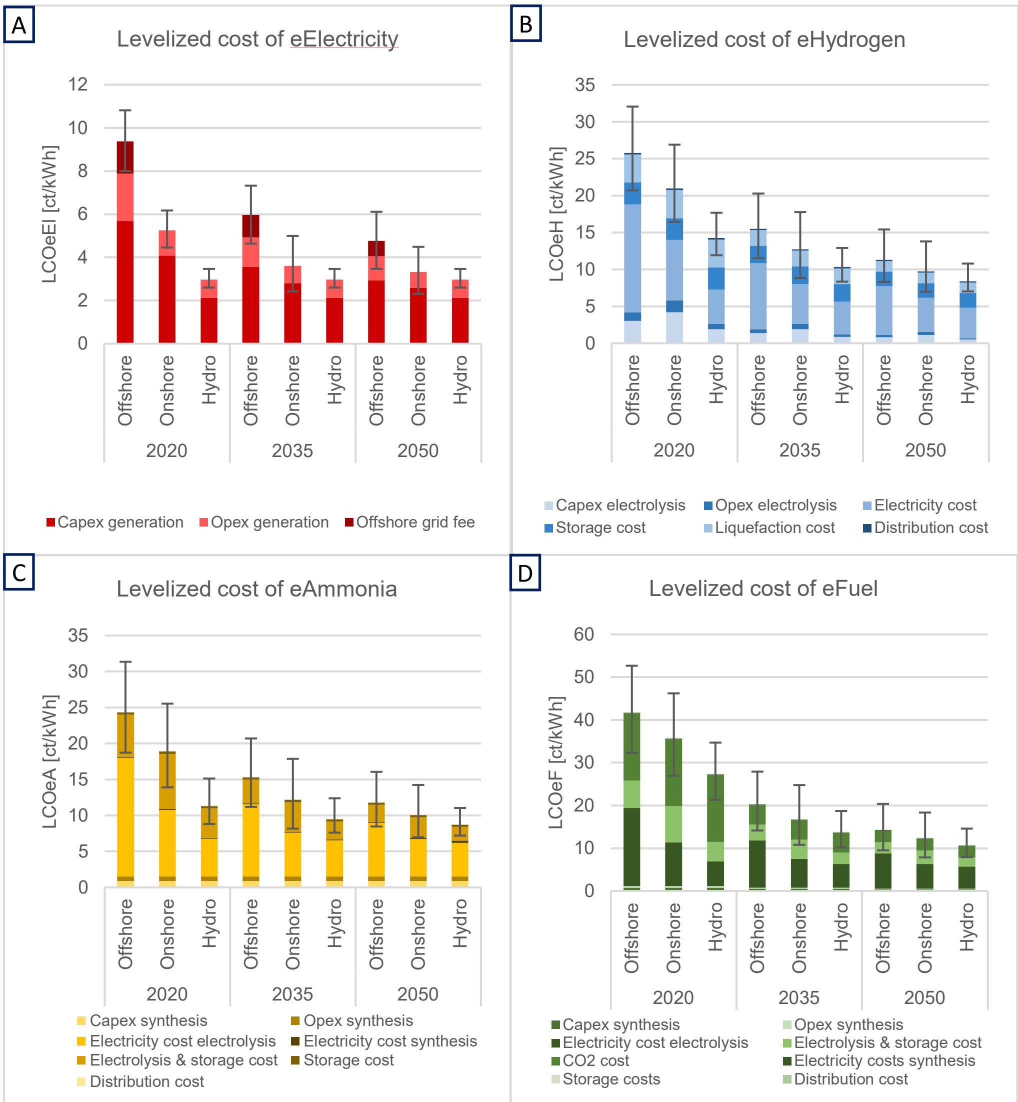

Figure 2 Levelized cost of eElectricity [A], eHydrogen [B], eAmmonia [C] and eFuel [D] considering different renewable electricity sources 2020-2050. The electricity costs calculated in A negatively affect the fuel costs in B, C and D. The electrolysis and liquefaction costs negatively affect the eHydrogen cost (note: ~50% cost reduction potential for eH until 2050). The CO_2 direct air capture cost and low energy efficiency in production negatively affect the eFuel cost. Comparatively, the cheaper cost of nitrogen and liquefaction positively affects the eAmmonia cost. Shown distribution costs only include 500 km ship distribution. The error bars show the maximum uncertainty included for the selected parameters. See SI for the details. (Source: own illustration)

Levelized cost of transport: long-haul trucking

For long-haul trucking, we assume a common 40 tonne semi-truck[4] with truck unit and separate cargo semi-trailer, investigate compressed eH and eF (Figure 1) and compare them to the fF, truck diesel. We assume a fuel station network with all stations having a maximal fuel output of 43 GWh/a and we add their levelized costs to the LCOF. For eHydrogen, we calculate the fuel station costs with an increasing utilization rate, 70%, 85% and 100% in 2020, 2035 and 2050, respectively. We assume a fuel-cell truck with 700 bar storage tanks[4] and an increasing fuel cell efficiency[5,16]. For fF and eF, we assume identical trucks with internal combustion engine and a constant fuel demand. To determine the total cost of ownership per tonne-kilometre, we consider additional costs to deliver freight by long-haul trucking. See the levelized cost (LCOTT) in Figure **3**.

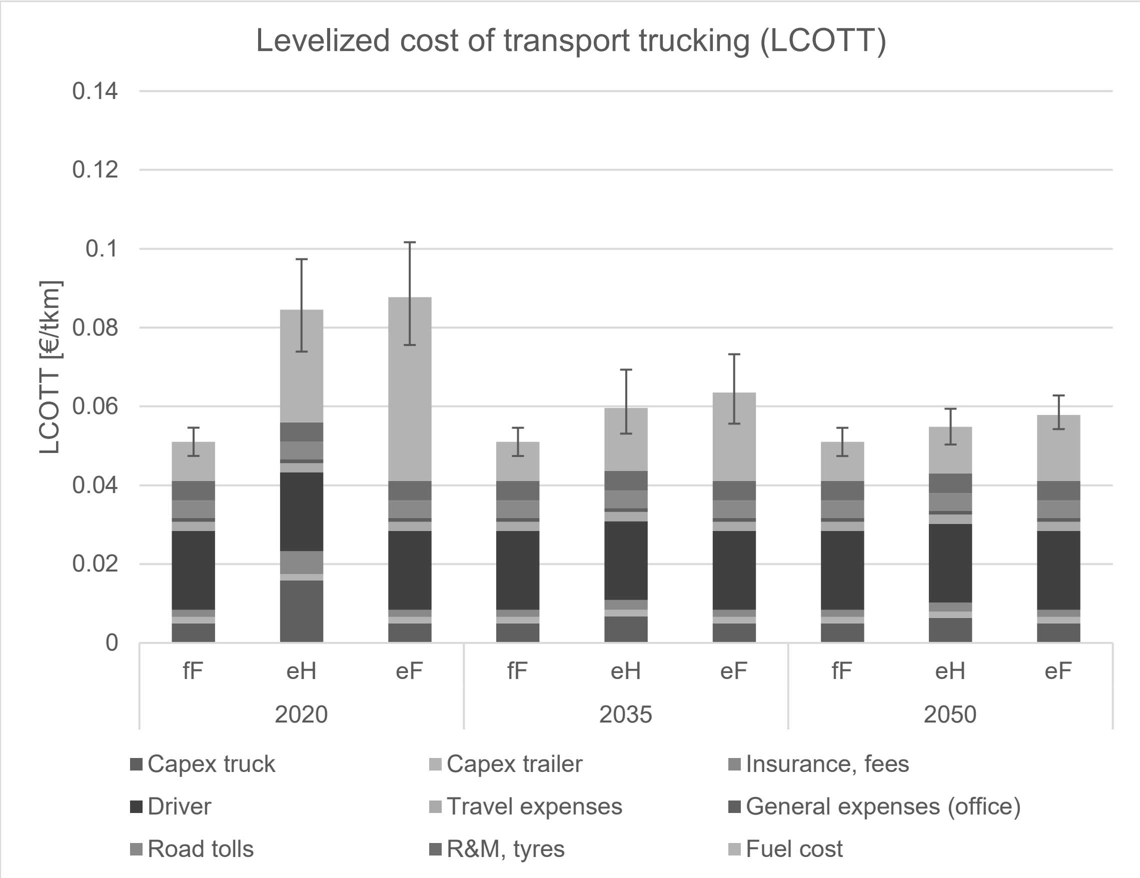

Figure 3 Levelized cost of transport trucking (LCOTT) considering fossil fuel (fF), eHydrogen (eH) and eFuel (eF) as fuel options based on electricity from onshore wind. In the first years, high Capex and hydrogen fuel costs affect the eH case, but as the costs decrease over time, hydrogen trucks become almost as competitive as the fF trucks. Fuel costs affect the eF case, having the same vehicle Capex as the fF case. All costs without taxes and subsidies. Error bars show the maximum uncertainties of fuel costs and vehicle technologies. See SI for the details. (Source: own illustration)

Levelized cost of transport: short-sea shipping

For short-sea shipping we assume an internationally representative midsized container ship with 9,450 deadweight tonnes and an installed power of 7,200 kW[41]. We investigate the use of eH, eA and eF and compare them to fF, heavy fuel oil (HFO). The analysed fuels are all directly bunkered (tank ship to end-use ship) to avoid additional refuelling infrastructure. For fF and eF, we assume identical ships and a constant fuel demand[4,8,9]. For eH and eA, we assume fuel-cell ships with liquid fuel storage[4,8,9] and increasing fuel cell efficiency[16] to be available by 2030[9]. To determine the total cost of ownership per tonne-kilometre, we consider additional costs to deliver freight by short-sea shipping. See the levelized cost (LCOTS) in Figure 4.

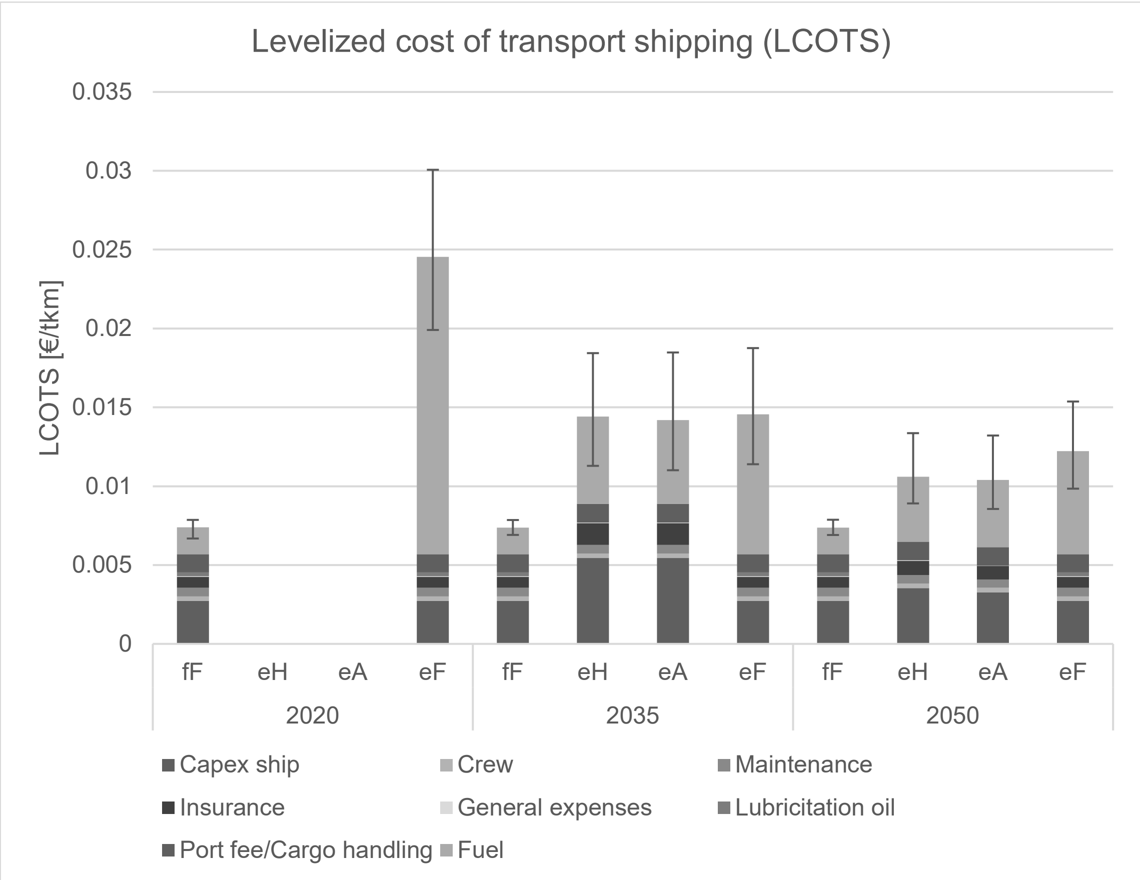

Figure 4 Levelized cost of transport shipping (LCOTS) considering fossil fuel (fF), eHydrogen (eH), eAmmonia (eA) and eFuel (eF) as fuel options based on electricity from onshore wind. The eH and eA cases are assumed to be available only as of 2035. High Capex and fuel costs affect the eH and eA case, but as the costs decrease over time, both options become more attractive. Fuel costs affect the eF case, which uses the same vehicle Capex as the fF case. In the mid-term, eFuel-based shipping potentially is a bridge technology, but less so in the later years. All costs without taxes and subsidies. Error bars show the maximum uncertainties of fuel costs and vehicle technologies. See SI for the details. (Source: own illustration)

Levelized cost of transport: short-haul aviation

For short-haul aviation we assume a plane with 73.5t maximum take-off weight and a maximum payload of 20 tonnes, comparable to a narrow-body freighter A320[4,42]. We investigate the use of eH and eF and compare it to fF, jet A-1. The analysed fuels are all directly bunkered (tank truck to aircraft) to avoid additional refuelling infrastructure[13]. For fF and eFuel, we assume an identical aircraft and constant fuel demand. The use of eF is assumed as a 100% fF substitution (no fuel blending). For eH, we assume an aircraft with modified jet engines and liquid hydrogen tanks to be available by 2035[43]. We consider the same fuel consumption for hydrogen engines[13] but reduce the payload capacity by 25% due to the volume and mass of cryotanks[4,11,13]. To determine the total cost of ownership per tonne-kilometre, we consider additional costs to deliver freight by short-haul aviation. See the levelized cost (LCOTA) in Figure 5.

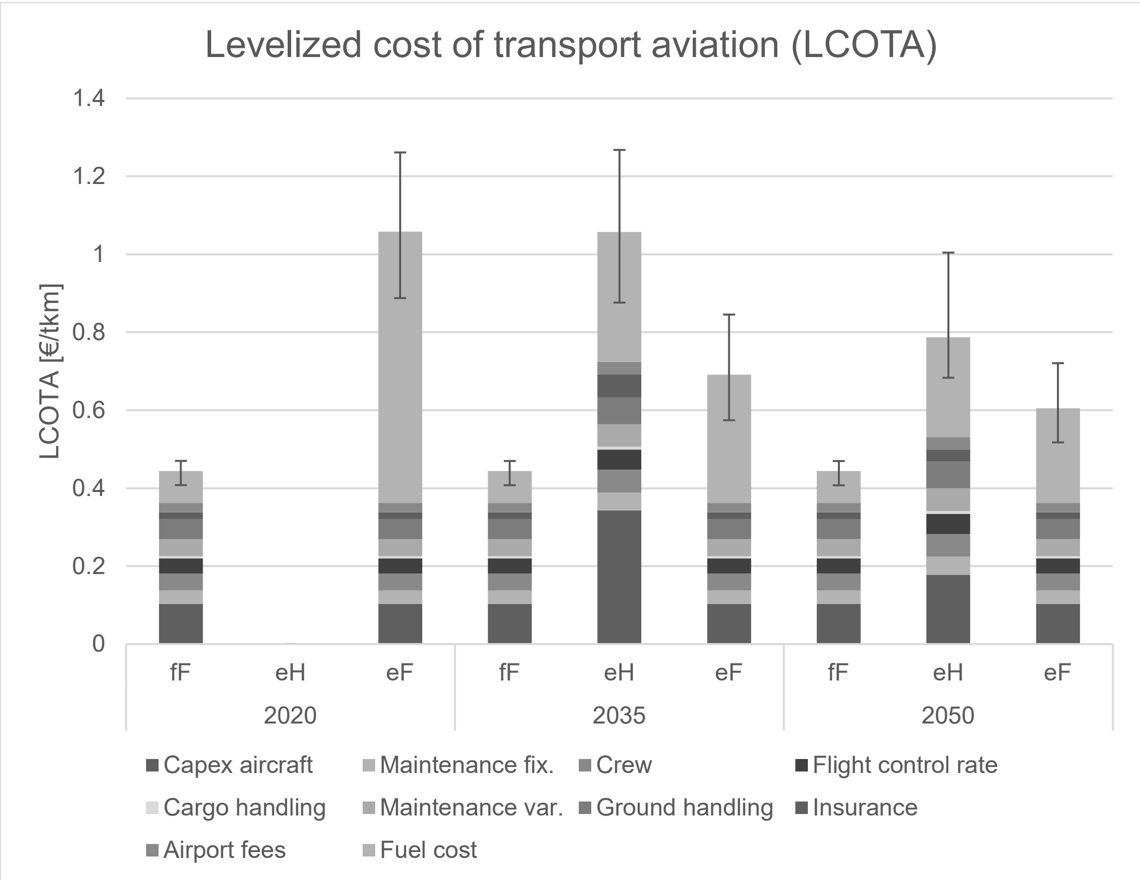

Figure 5 Levelized cost of transport aviation (LCOTA) considering fossil fuel (fF), eHydrogen (eH) and eFuel (eF) as fuel options based on electricity from onshore wind. The eH case is assumed to be available only as of 2035. Limited cargo space, high Capex and hydrogen fuel costs affect the eH case, with clear cost disadvantages up to 2050. Fuel costs affect the eF case, which uses the same aircraft Capex as the fF case. Due to limited fuel options with comparable energy density for aviation, eFuel has long-term potential if the market ramp-up and cost decreases occur as expected. All costs without taxes and subsidies. Error bars show the maximum uncertainties of fuel costs and vehicle technologies. See SI for the details. (Source: own illustration)

Competitiveness within the three transport modes

Figure **6** shows the three modes' preferred SHF choices and the respective transport cost sensitivity (percentual cost change due to fuel choice) compared to fF until 2050 based on figures **3, 4 and 5**. The details are as follows.

Decarbonizing short-haul aviation by using eF early has a transport cost sensitivity of +138% compared to fF, and aviation owners are under economic pressure to achieve early GHG reduction goals[44]. Fuel costs affect the eF case having the same aircraft Capex as the fF case. When eH enters the aviation market in 2035[43], the transport cost sensitivity is +138% and +77% in 2050. Capex and hydrogen fuel costs affect the eH case in combination with the limited cargo space due to volume and weight restrictions. As the costs decrease over time, hydrogen aircrafts become more attractive. Investments in hydrogen technology for sustainable aviation will increase transport cost in the mid-term and payload limitations require new operational practices. However, hydrogen aviation may provide beneficial diversification that minimizes the risk of fossil-fuel dependency if eF falls short of expectations. Specifically, the potential absence of early cost reduction of eF's carbon supply, would put the sector under unique cost pressure.

Decarbonizing long-haul trucking by using eH has a transport cost sensitivity of +66% in 2020 and +8% in 2050. In the first years, high Capex and hydrogen fuel costs affect the eH case, but as the costs decrease over time, hydrogen trucks become almost as competitive as the fF trucks. Fuel costs affect the eF case, having the same vehicle Capex as the fF case. Decarbonizing existing fleets by using eF is economically unattractive due to the

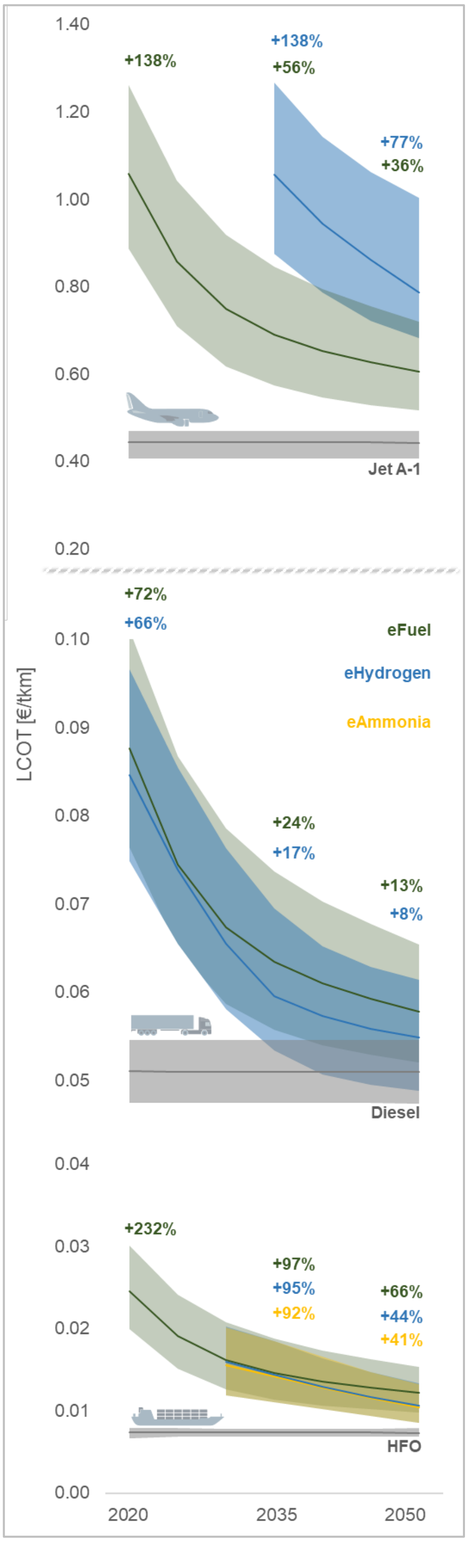

Figure 6: Change of levelized cost of transport in percentages for aviation, trucking and shipping (grouped from top) considering fuel options based on electricity from onshore wind. Transport costs within and across modes change asymmetrically over time. Percentages show the cost gap of alternatives (base-case) benchmarked to the sector-specific fossil fuel case. Shadows show the maximum uncertainties of fuel costs and vehicle technologies (fF uncertainty represents the historical fluctuation of fF cost). All shown costs without taxes and subsidies. (Source: own illustration)

dominant share of fuel cost compared to vehicle Capex in total cost of ownership and short investment cycles.

Decarbonizing short-sea shipping by using eF early has a transport cost sensitivity of +232% compared to fF, and shipowners are under economic pressure to achieve early GHG reduction goals[45]. Fuel costs affect the eF case, having the same vehicle Capex as the fF case. However, with typical long-term investments of more than 25 years[8], eFuel could be attractive to decarbonize existing ship fleets. When both eA and eH enter the maritime market around 2030[9], transport cost sensitivities are +92% or +95% in 2035 and +41% or +44% in 2050, for eA and eH, respectively. eA-based shipping has easier fuel handling and storage[4,10] but slower cost reductions for ammonia fuel-cells[19], whereas eH-based shipping has complex fuel handling and storage[4] but faster cost reductions for hydrogen fuel cells due to synergies with other markets[16]. The choice of fuel will also depend on its availability and handling in the international port environment.

Competitiveness across the transport modes

While criteria such as transport time, frequency, payload capacity and flexibility also determine the choice of freight transport, asymmetric cost changes across the transport modes can jeopardize the competitiveness of certain use cases and can lead to modal shift. Although shipping remains the cheapest and aviation the most expensive mode, the introduction of alternative fuels mostly affects shipping due to today's low cost of heavy fuel oil and thus the steepest cost rise toward alternative fuels. Whereas for trucking, optimal SHF choices increase transport cost by only a factor of about 0.66, 0.17 and 0.08 in 2020, 2035 and 2050, respectively, for aviation transport costs increase by a factor of about 1.38, 0.56, 0.36 and for shipping by a factor of 2.32, 0.92, 0.41 in 2020, 2035 and 2050. Beside fuel costs, the technology Capex affect the transport modes asymmetrically. The integration of eH-based aviation to differentiate decarbonization options around 2035 causes an additional cost peak for operators. See Table **2** (Appendix) for shift-dependent changes in levelized cost of transport in € per tonne-kilometre within and across transport modes.

Effects of changing electricity generation sources across the modes

Having identified electricity as one of the most significant cost drivers, we model the effects of changing the renewable electricity sources for fuel production. See Figure **7** in the Appendix. Hydropower generation benefits all SHF because it reduces the levelized cost of transport for all fuel and mode combinations. Shipping is the most sensitive to the choice of electricity sources due to the most unfavourable fuel substitutes' cost ratio (SHF to HFO). The use of eF mostly benefits from lower electricity costs due to the multiplicative effect of efficiency losses in production and consumption. The cost decrease facilitates an early business case for eF in long-haul trucking. Even though more hydropower generation can stimulate early SHF markets, multi-year construction periods[35], negative effects on local hydrologic balance[46] and high energy efficiency losses particularly in eF production[15] continue. Offshore wind generation guarantees large quantities of electricity with high full load hours, but with the highest costs for decarbonizing transport.

We develop a dynamic cost model to compare the levelized costs of sustainable hydrogen fuels and transport options for long-haul trucking, short-sea shipping and short-haul aviation and identify the economic challenges of decarbonizing heavy-duty transport by 2050. We apply the model to Norway, which has excellent renewable energy potential and is considered an early adopter of sustainable transport. We model the value chains for the alternative fuels, hydrogen, hydrocarbon and ammonia. We show the changes in the fuels' competitiveness caused by changes in the costs of electricity generation and vehicle and fuel technology, benchmarked against freight transport's fossil-based counterparts from 2020 to 2050.

Considering onshore wind generation as potentially low-cost, we find that the three transport modes will suffer cost disadvantages when using sustainable hydrogen fuels compared to fossil fuels. For decarbonization, the results reveal the most favourable fuel choices for each mode: eHydrogen for trucking, eFuel in the early years and eAmmonia starting in 2030 for shipping and eFuel for aviation. The existing cost rankings are maintained over the time period: shipping remains the cheapest, whereas aviation is the most expensive. Shipping has the highest transport cost sensitivity due to the most unfavourable fuel substitutes' cost ratio.

Lower costs of electricity depending on the choice of renewable electricity generation significantly affects the levelized cost of transport. eFuel reacts most to lower electricity costs, due to the multiplicative effect of efficiency losses in production and consumption. Offshore wind creates the highest cost of transport. Onshore wind leads to lower transport costs, but strong opposition to siting limits its expansion. A restricted expansion of hydropower encourages early market introduction, especially for eF-based transport which depends on early low-cost electricity to meet a short window of opportunities.

We conclude that by betting on learning curves and substantial cost decreases of technologies needed along the value chain, heavy-duty transport decarbonization by 2050 cannot be achieved. Although the cost gaps to fossil-based transport decrease over time, we see that decarbonization pathways for freight transport are out of reach without government intervention. Future research is needed to identify optimal public and private support throughout the value chains. Evaluating asymmetric changes in transport costs and its implication on modal shift is another important research topic.

Method

To compare fuel and transport alternatives, we apply the concept of levelized cost of energy (LCOE, equation 3), which conventionally assigns a power plant's total lifecycle cost (TLCC) to one unit of energy output[31]. *TLCC* include capital costs, fuel costs, fixed and variable operations and maintenance (O&M) costs, financing costs, and a utilization rate. To cover *TLCC* over the equipment's financial life, *LCOE* represents the discounted average revenue per unit required to break even[30] which we formulate as:

$$\sum_{n=1}^{N} \frac{Q_n * LCOE}{(1+d)^n} = TLCC \ , \tag{3}$$

where Q_n is the energy output per year n, d is the discount rate and N is the analysis period in years. *LCOE* is commonly used to compare and rank investment alternatives in power generation when there are different scales of operation, investment or operating time periods[31].

We generalize the formula to calculate the levelized costs of an arbitrary process throughout the value chain denoted as LCOX (equations 4–6). System output Q remains constant over N. Our dynamic cost model, which can be tailored to local conditions with reference to the value-adding processes (Figure **1**) obtains the levelized costs of electricity (LCOEl, equation 14), fuel production with distribution (LCOF, equations 7–13) and transport services (LCOT, equations 15–17). We extent TLCC to total cost of ownership (TCO) where needed. Using a uniform capital recovery factor (UCRF) for the entire period, we reformulate and reduce the equation as:

$$LCOX = \frac{TLCC_X * UCRF}{Q_X} \ , \tag{4}$$

where $TLCC_X$ are the total lifecycle cost of an arbitrary process X (i.e., electricity or hydrogen production) and Q_x is the constant annual output of X per year.

We use *UCRF* to calculate a uniform series of annual payments over lifetime N, which are equivalent to the existing TLCC[31]. The interest rate is the weighted average cost of capital *WACC*, which is the average rate paid by a company to all security holders to finance assets and cover the risk of investment:

$$UCRF = \frac{WACC * (1+WACC)^N}{(1+WACC)^N - 1} \ . \tag{5}$$

We neglect inflation and assume constant operation and maintenance cost over N, disentangling TLCC into its components:

$$LCOX = \frac{Capex_x * UCRF + Opex_{x,fix}}{Q_x} + Opex_{x,var} \ , \tag{6}$$

where $Capex_x$ are the capital expenditures, $Opex_{x,fix}$ are the fixed operational expenditures per year and $Opex_{x,var}$ are the variable operational expenditures per output unit for an arbitrary process *X*. We use equation (6) to formulate the process-specific calculations.

Levelized cost of fuel (LCOF)

First, we apply LCOX to the levelized cost of fuel (LCOF) to compare the competitiveness of fF, eH, eA and eF. We disentangle LCOF in the levelized cost of fuel delivery (LCOD) and the levelized cost of fuel production (LCOP):

$$LCOF = LCOD + LCOP \ , \tag{7}$$

with

$$LCOD = LCOR + LCODi + LCOS_{fuel} \, , \tag{8}$$

to obtain LCOD by the levelized cost of refuelling (LCOR) plus levelized cost of fuel distribution (LCODi) and levelized cost of fuel buffer storage ($LCOS_{fuel}$).

We calculate LCOR by applying the LCOX pattern to fuel station *R*, with $Q_{R,max}$ as the maximal fuel output at the fuel station per year and UR_R as the station's average utilization rate:

$$LCOR = \frac{Capex_R * UCRF + Opex_{R,fix}}{Q_{R,max} * UR_R} \ . \tag{9}$$

We calculate LCODi by fuel trucks following equation (15-17), and LCODi by fuel ships and $LCOS_{fuel}$ applying literature values.

We use equation (10-11) to obtain LCOP by the levelized cost of fuel transformation (LCOTr), plus levelized cost of reactants ($LCORe_P$), plus levelized cost of hydrogen ($LCOH_P$) for the production process P:

$$LCOP = LCOTr + LCORe_P + LCOH_P \ . \tag{10}$$

$$LCOP = \frac{Capex_{Tr} * UCRF + Opex_{Tr,fix}}{Q_{Tr,Flh}} + Opex_{Tr,var} + \frac{LCORe}{\eta_{P,Re}} + \frac{LCOH}{\eta_{P,H}} \ . \tag{11}$$

We use equation (11) to obtain LCOP by applying the LCOX pattern to a transformation process (including fuel synthesis and liquefaction) with $Q_{Tr,Flh}$ as the average output per year in full load hours, plus levelized cost of reactant (nitrogen or carbon), plus levelized cost of hydrogen (LCOH), with $\eta_{P,Re}$ and $\eta_{P,H}$ as efficiency in the production process. For the fuel path eH, no synthesis process and reactant are required, but here LCOTr describes the levelized cost of hydrogen liquefaction.

We use equation (12) to obtain LCOH determined by the levelized cost of electrolysis (LCOEy) plus $LCOS_{cav}$ as the hydrogen storage cost in caverns, the latter based in literature values:

$$LCOH = LCOEy + LCOS_{cav} \quad , \tag{12}$$

and use equation (13) to obtain LCOEy by applying the LCOX pattern to an electrolysis process with $Q_{Ey,Flh}$ as the average output per year in full load hours. We use renewable electricity as the feedstock, factored as the levelized cost of electricity (LCOEl) with $\eta_{Ey,El}$ as efficiency in the electrolysis process. We neglect the second feedstock and its water costs:

$$LCOEy = \frac{Capex_{Ey} * UCRF + Opex_{Ey,fix}}{Q_{Ey,Flh}} + Opex_{Ey,var} + \frac{LCOEl}{\eta_{Ey,El}} \ . \tag{13}$$

We use equation (14) to obtain LCOEl by applying the LCOX pattern to a generator of renewable electricity (hydro, offshore wind or onshore wind) with $Q_{El,Flh}$ as the average output per year in full load hours. For offshore wind, $Opex_{El,var}$ includes the grid connection cost to the mainland:

$$LCOEl = \frac{Capex_{El} * UCRF + Opex_{El,fix}}{Q_{El,Flh}} + Opex_{El,var} \ . \tag{14}$$

Levelized cost of transport (LCOT)

We use equation (15) to obtain the levelized cost of transport LCOT by the levelized cost of vehicle (LCOV) plus $Opex_{sup,var}$ as the supporting cost per unit. The supporting cost per unit include for example administrative, infrastructure fees or cargo handling costs which supplement the total cost of ownership.

We use equation (16) to obtain LCOV by applying the LCOX pattern to a truck, ship or plane with $Q_{V,tkm}$ as the average mileage per year in tonne-kilometre. We use equation (17) to obtain $Q_{V,tkm,}$ by AM_V as the annual vehicle mileage, $CC_{V,max}$ as the maximum cargo capacity per conventional vehicle and UR_V as the utilization rate per alternative vehicle. UR_V is important because higher tank volumes or mass restrictions for some fuel alternatives can reduce cargo holds. We use the calculated fuels (fF, eH, eA, eF), factored as the levelized cost of fuel (LCOF), with $\eta_{V,F}$ as a vehicle's fuel efficiency:

$$LCOT = LCOV + Opex_{sup,var} \ , \qquad (15)$$

$$LCOV = \frac{Capex_V * UCRF + Opex_{V,fix}}{Q_{V,Tkm}} + Opex_{V,var} + \frac{LCOF}{\eta_{V,F}} \ \text{, and} \qquad (16)$$

$$Q_{V,Tkm} = AM_V * CC_{V,max} * UR_V \ . \qquad (17)$$

Data and sensitivity analysis

Our cost estimations have a time resolution of five years from 2020 to 2050, based on publicly available data and interpolations. We collect data for 140 parameters from articles in peer-reviewed scientific journals and frequently cited reports by consultants, agencies and industry experts, validated by practitioners. We investigate the uncertainties of future cost values in worst-, base- and best-case scenarios, and include them in Figures **2–7**. Parameters considered in the sensitivity analysis are: Capex and full load hours of onshore, offshore wind and hydropower (full load hours only), electrolysis Capex and efficiency, CO_2 direct air capture Capex, hydrocarbon synthesis Capex, ammonia synthesis Capex, hydrogen liquefaction Capex, and vehicle technology Capex and efficiency (alternatives only). See SI for the details.

Appendix

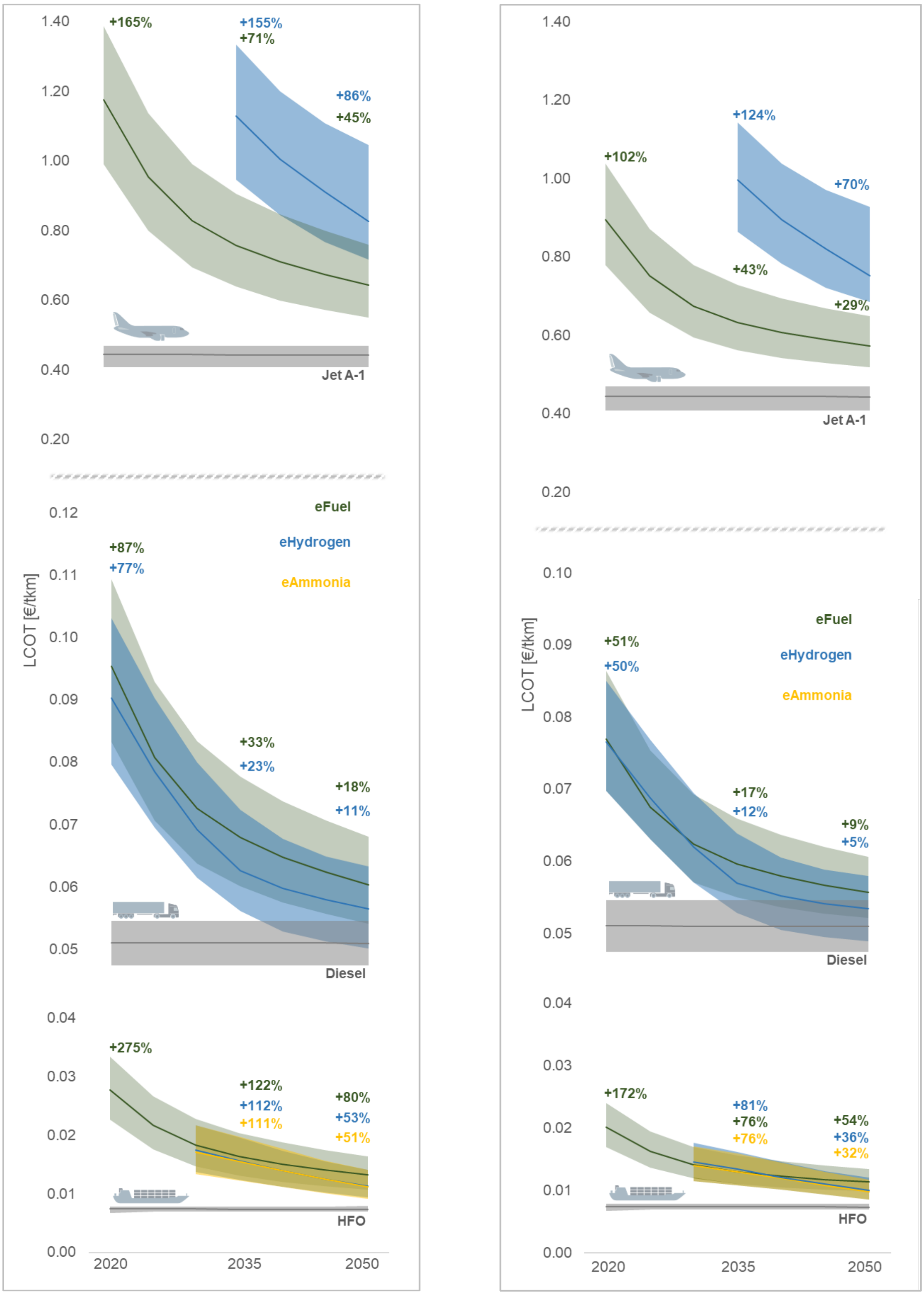

Figure 7 Change of levelized cost of transport in percentages considering fuel alternatives for aviation, trucking and shipping due to different renewable energy sources, offshore wind (left), hydropower (right). Transport costs within and across modes change asymmetrically over time. Percentages show the cost gap of alternatives (base-case) benchmarked to the sector-specific fossil fuel case. Offshore wind power with highest electricity costs and hydropower with lowest significantly affect early eFuel-based transport and change the total transport cost level. Shadows show the maximum uncertainties of fuel costs and vehicle technologies (fF uncertainty represents the historical fluctuation of fF cost). All shown costs without taxes and subsidies. (Source: own illustration)

All values in €/tkm

Transport A		Transport B									
	2020	A_fF	A_eH	A_eF	T_fF	T_eH	T_eF	S_fF	S_eH	S_eA	S_eF
	A_fF	0.000		0.614	-0.393	-0.360	-0.356	-0.437			-0.420
	A_eH										
	A_eF	-0.614		0.000	-1.007	-0.973	-0.970	-1.051			-1.033
	T_fF	0.393		1.007	0.000	0.034	0.037	-0.044			-0.026
	T_eH	0.360		0.973	-0.034	0.000	0.003	-0.077			-0.060
	T_eF	0.356		0.970	-0.037	-0.003	0.000	-0.080			-0.063
	S_fF	0.437		1.051	0.044	0.077	0.080	0.000			0.017
	S_eH										
	S_eA										
	S_eF	0.420		1.033	-0.037	0.060	0.063	-0.017			0.000

Transport A		Transport B									
	2035	A_fF	A_eH	A_eF	T_fF	T_eH	T_eF	S_fF	S_eH	S_eA	S_eF
	A_fF	0.000	0.614	0.247	-0.393	-0.384	-0.380	-0.436	-0.429	-0.430	-0.429
	A_eH	-0.614	0.000	-0.367	-1.007	-0.998	-0.994	-1.050	-1.043	-1.044	-1.043
	A_eF	-0.247	0.367	0.000	-0.640	-0.631	-0.627	-0.684	-0.676	-0.677	-0.676
	T_fF	0.393	1.007	0.640	0.000	0.009	0.012	-0.044	-0.037	-0.037	-0.036
	T_eH	0.384	0.998	0.631	-0.009	0.000	0.004	-0.052	-0.045	-0.045	-0.045
	T_eF	0.380	0.994	0.627	-0.012	-0.004	0.000	-0.056	-0.049	-0.049	-0.049
	S_fF	0.436	1.050	0.684	0.044	0.052	0.056	0.000	0.007	0.007	0.007
	S_eH	0.429	1.043	0.676	0.037	0.045	0.045	-0.007	0.000	0.000	0.000
	S_eA	0.430	1.044	0.677	0.037	0.045	0.045	-0.007	0.000	0.000	0.000
	S_eF	0.429	1.043	0.676	-0.012	0.045	0.049	-0.007	0.000	0.000	0.000

Transport A		Transport B									
	2050	A_fF	A_eH	A_eF	T_fF	T_eH	T_eF	S_fF	S_eH	S_eA	S_eF
	A_fF	0.000	0.343	0.162	-0.393	-0.389	-0.386	-0.436	-0.433	-0.433	-0.431
	A_eH	-0.343	0.000	-0.182	-0.736	-0.732	-0.729	-0.780	-0.777	-0.777	-0.775
	A_eF	-0.162	0.182	0.000	-0.554	-0.550	-0.547	-0.598	-0.595	-0.595	-0.593
	T_fF	0.393	0.736	0.554	0.000	0.004	0.007	-0.044	-0.040	-0.041	-0.039
	T_eH	0.389	0.732	0.550	-0.004	0.000	0.003	-0.047	-0.044	-0.044	-0.043
	T_eF	0.386	0.729	0.547	-0.007	-0.003	0.000	-0.050	-0.047	-0.047	-0.046
	S_fF	0.436	0.780	0.598	0.044	0.047	0.050	0.000	0.003	0.003	0.005
	S_eH	0.433	0.777	0.595	0.040	0.044	0.044	-0.003	0.000	0.000	0.002
	S_eA	0.433	0.777	0.595	0.041	0.044	0.044	-0.003	0.000	0.000	0.002
	S_eF	0.431	0.775	0.593	-0.007	0.043	0.046	-0.005	-0.002	-0.002	0.000

Table 2 Shift-dependent change in levelized cost of transport A to transport B (base case scenario, electricity source: onshore wind). If transport B replaces transport A, the above changes in levelized costs of transport occur. Empty boxes show the non-availability of transport technologies. Dark grey boxes are replacements within a transport mode and light gray boxes are replacements across the transport modes. The cost delta decreases from 2020 to 2050 as the costs of new technologies and fuels decrease. All shown costs without taxes and subsidies. Aviation (A), trucking (T), shipping (S), fossil Fuel (fF), eHydrogen (eH), eAmmonia (eA), eFuel (eF). (Source: own illustration)

Data availability

The data used in this study are referenced in the main body of the paper and the Supplementary Information. Data that generated the plots in the paper are provided in the Supplementary Information.

Code availability

Additional information including the code are available from the corresponding author upon reasonable request.

Acknowledgements

This work was carried out within MoZEES, a Norwegian Centre for Environment friendly Energy Research (FME), co-sponsored by the Research Council of Norway (project number 257653) and 40 partners from research, industry and public sector.

Author contributions

The authors jointly developed the research question, the model framework and the analytical findings. J.M. led the literature review, the data collection and the calculations. All three authors contributed substantially to the writing of the paper.

Competing interests

The authors declare no competing interests.

References

1. IRENA. *Global renewables outlook. Energy transformation 2050* (IRENA, Abu Dhabi, 2020).

2. IPCC. Climate change 2022. Impacts, adaption and vulnerability - Summary for policymakers. Available at https://report.ipcc.ch/ar6wg2/pdf/IPCC_AR6_WGII_FinalDraft_FullReport.pdf (2022).

3. Miller, M., Wang, Q. & Fulton, L. *Truck choice modeling. Understanding California's transition to zero-emission vehicle trucks taking into account truck technologies, costs, and fleet decision behavior* (UC Davis: National Center for Sustainable Transportation, Davis, 2017).

4. Gray, N., McDonagh, S., O'Shea, R., Smyth, B. & Murphy, J. D. Decarbonising ships, planes and trucks. An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. *Advances in Applied Energy* **1**; 10.1016/j.adapen.2021.100008 (2021).

5. Cunanan, C. *et al.* A review of heavy-duty vehicle powertrain technologies. Diesel engine vehicles, battery electric vehicles, and hydrogen fuel cell electric vehicles. *Clean Technol.* **3,** 474–489; 10.3390/cleantechnol3020028 (2021).

6. Transport & Environment. *How to decarbonise long-haul trucking in Germany. An analysis of available vehicle technologies and their associated costs.* (Brussel, 2021).

7. Horvath, S., Fasihi, M. & Breyer, C. Techno-economic analysis of a decarbonized shipping sector. Technology suggestions for a fleet in 2030 and 2040. *Energy Conversion and Management* **164,** 230–241; 10.1016/j.enconman.2018.02.098 (2018).

8. Taljegard, M., Brynolf, S., Grahn, M., Andersson, K. & Johnson, H. Cost-effective choices of marine fuels in a carbon-constrained world. Results from a global energy model. *Environmental science & technology* **48,** 12986–12993; 10.1021/es5018575 (2014).

9. Hansson, J., Brynolf, S., Fridell, E. & Lehtveer, M. The potential role of ammonia as marine fuel. Based on energy systems modeling and multi-criteria decision analysis. *Sustainability* **12,** 3265; 10.3390/su12083265 (2020).

10. Cheliotis, M. *et al.* Review on the safe use of ammonia fuel cells in the maritime industry. *Energies* **14,** 3023; 10.3390/en14113023 (2021).

11. Baroutaji, A., Wilberforce, T., Ramadan, M. & Olabi, A. G. Comprehensive investigation on hydrogen and fuel cell technology in the aviation and aerospace sectors. *Renewable and Sustainable Energy Reviews* **106,** 31–40; 10.1016/j.rser.2019.02.022 (2019).

12. Yilmaz, N. & Atmanli, A. Sustainable alternative fuels in aviation. *Energy* **140,** 1378–1386 (2017).

13. McKinsey & Company. *Hydrogen-powered aviation. A fact-based study of hydrogen technology, economics, and climate impact by 2050* (FCH 2 JU; Clean Sky 2 JU, Luxembourg, 2020).

14. Brynolf, S., Taljegard, M., Grahn, M. & Hansson, J. Electrofuels for the transport sector. A review of production costs. *Renewable and Sustainable Energy Reviews* **81,** 1887–1905; 10.1016/j.rser.2017.05.288 (2018).

15. Ueckerdt, F. *et al.* Potential and risks of hydrogen-based e-fuels in climate change mitigation. *Nature Climate Change* **11,** 384–393; 10.1038/s41558-021-01032-7 (2021).

16. Cullen, D. A. *et al.* New roads and challenges for fuel cells in heavy-duty transportation. *Nature Energy* **6,** 462–474; 10.1038/s41560-021-00775-z (2021).

17. Fasihi, M., Weiss, R., Savolainen, J. & Breyer, C. Global potential of green ammonia based on hybrid PV-wind power plants. *Applied Energy* **294,** 116170; 10.1016/j.apenergy.2020.116170 (2021).

18. Glenk, G. & Reichelstein, S. Economics of converting renewable power to hydrogen. *Nature Energy* **4,** 216–222; 10.1038/s41560-019-0326-1 (2019).

19. Lan, R. & Tao, S. Ammonia as a suitable fuel for fuel cells. *Frontiers in Energy Research* **2,** 1–4; 10.3389/fenrg.2014.00035 (2014).

20. Ryste, J. A. *Comparison of alternative marine fuels* (DNV GL AS Maritime, Høvik, 2019).

21. Fasihi, M. & Breyer, C. Baseload electricity and hydrogen supply based on hybrid PV-wind power plants. *Journal of Cleaner Production* **243,** 118466; 10.1016/j.jclepro.2019.118466 (2020).

22. Reuß, M. *et al.* Seasonal storage and alternative carriers. A flexible hydrogen supply chain model. *Applied Energy* **200,** 290–302; 10.1016/j.apenergy.2017.05.050 (2017).

23. Hank, C. *et al.* Energy efficiency and economic assessment of imported energy carriers based on renewable electricity. *Sustainable Energy Fuels* **4,** 2256–2273; 10.1039/D0SE00067A (2020).

24. Nayak-Luke, R., Bañares-Alcántara, R. & Wilkinson, I. "Green" ammonia. Impact of renewable energy intermittency on plant sizing and levelized cost of ammonia. *Ind. Eng. Chem. Res.* **57,** 14607–14616; 10.1021/acs.iecr.8b02447 (2018).

25. Agora Verkehrswende, Agora Energiewende & Frontier Economics. *The future cost of electricity-based synthetic fuels* (frontier economics, Berlin, 2018).

26. Boer, E. den, Aarnink, S., Kleiner, F. & Pagenkopf, J. *Zero emissions trucks. An overview of state-of-the-art technologies and their potential* (CE Delft, 2013).

27. Stenning, J. *et al. Trucking into a Greener Future. The economic impact of decarbonizing goods vehicles in Europe* (Cambridge econometrics, Cambridge, 2018).

28. Noll, B., Del Val, S., Schmidt, T. S. & Steffen, B. Analyzing the competitiveness of low-carbon drive-technologies in road-freight. A total cost of ownership analysis in Europe. *Applied Energy* **306,** 118079; 10.1016/j.apenergy.2021.118079 (2022).

29. Wiser, R. *et al.* Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050. *Nature Energy* **6,** 555–565; 10.1038/s41560-021-00810-z (2021).

30. Lai, C. S. & McCulloch, M. D. Levelized cost of electricity for solar photovoltaic and electrical energy storage. *Applied Energy* **190,** 191–203; 10.1016/j.apenergy.2016.12.153 (2017).

31. Short, W., Packey, D. J. & Holt, T. *A manual for the economic evaluation of energy efficiency and renewable energy technologies* (National Renewable Energy Laboratory, Golden, 1995).

32. Norwegian Government. Opening of the areas Utsira Nord and Sørlige Nordsjø II for processing of applications for licences for renewable energy production pursuant to the offshore energy act. Case no: 20/88- (Unofficial translation). Available at

https://www.regjeringen.no/contentassets/aaac5c76aec242f09112ffdceabd6c64/royal-decree-opening-of-areas-june-2020.pdf (2020).

33. Staffell, I. & Pfenninger, S. Using bias-corrected reanalysis to simulate current and future wind power output. *Energy* **114,** 1224–1239; 10.1016/j.energy.2016.08.068 (2016).

34. NVE. NVE Atlas - Data sheet Aura hydropower. Available at https://www.nve.no/energi/energisystem/vannkraft/vannkraftdatabase/vannkraftverk/ ?id=9 (2021).

35. IRENA. *Hydropower. Renewable energy technologies: Analysis series* (IRENA, Bonn, 2012).

36. Ahluwalia, R., Papadias, D., Peng, J. & Roh, H. System level analysis of hydrogen storage options. Available at https://www.hydrogen.energy.gov/pdfs/review19/st001_ahluwalia_2019_o.pdf (2019).

37. Brinner, A., Schmidt, M., Schwarz, S., Wagener, L. & Zuberbühler, U. *Technologiebericht 4.1 Power-to-gas (Wasserstoff). Technologien für die Energiewende. Teilbericht 2 an das Bundesministerium für Wirtschaft und Energie (BMWi)* (Wuppertal Institut; ISI; IZES, Wuppertal, 2018).

38. Andersson, J. & Grönkvist, S. Large-scale storage of hydrogen. *International Journal of Hydrogen Energy* **44,** 11901–11919; 10.1016/j.ijhydene.2019.03.063 (2019).

39. Fasihi, M., Efimova, O. & Breyer, C. Techno-economic assessment of CO2 direct air capture plants. *Journal of Cleaner Production* **224,** 957–980; 10.1016/j.jclepro.2019.03.086 (2019).

40. Tollefson, J. Sucking carbon dioxide from air is cheaper than scientists thought. Available at https://www.nature.com/articles/d41586-018-05357-w (2018).

41. IMO. *Fourth IMO greenhouse gas study 2020* (International Maritime Organization, London, 2021).

42. EFW. A320/A321P2F. The new Airbus narrowbody freighter family. Available at https://www.elbeflugzeugwerke.com/fileadmin/pdfs/efw-druck-brochure-A320-02-Screen.pdf (2021).

43. AIRBUS. Airbus reveals new zero-emission concept aircraft. Press release. Available at file:///C:/Users/jonamar/Downloads/d82a792c20d166f4700d20c013fead8a_EN-Airbus-unveils-ZEA-concepts.pdf (2020).

44. Larsen, O. M. *et al.* Aviation in Norway. Sustainability and social benefit. Available at https://avinor.no/globalassets/_konsern/om-oss/rapporter/en/aviation-in-norway-sustainability-and-social-benefit-2020.pdf (2020).

45. Norwegian Shipowners' Association. Zero emissions in 2050. Available at https://rederi.no/en/aktuelt/2020/norwegian-shipping-climate-neutral-by-2050/ (2020).

46. Bakken, T. H., Sundt, H., Ruud, A. & Harby, A. Development of small versus large hydropower in Norway. Comparison of environmental impacts. *Energy Procedia* **20,** 185–199; 10.1016/j.egypro.2012.03.019 (2012).

Supplementary Information

SUSTAINABLE HYDROGEN FUELS VERSUS FOSSIL FUELS FOR TRUCKING, SHIPPING AND AVIATION: A DYNAMIC COST MODEL

Jonas Martin*[1], Anne Neumann[1], Anders Ødegård[2]

[1]Norwegian University of Science and Technology, Department of Industrial Economics and Technology Management, Trondheim, Norway | jonas.martin@ntnu.no, anne.neumann@ntnu.no

[2]SINTEF, Department of Sustainable Energy Technology, Trondheim, Norway| anders.odegard@sintef.no

List of abbreviations

ALK	Alkaline
a	Years
Bh	Block hours
Capex	Capital expenditures
CO_2	Carbon dioxide
ct	Eurocent
eA, eAmmonia	Electricity-based sustainable ammonia
eF, eFuel	Electricity-based sustainable hydrocarbon fuel
eH, eHydrogen	Electricity-based sustainable hydrogen
el	Electricity
fF, fFuel	Fossil-based fuel
fix	Fixed
GHG	Greenhouse gas emissions
GWh	Gigawatt-hours
h	Hours
H_2	Hydrogen
HFO	Heavy fuel oil
kg	Kilogram
km	Kilometre
kW	Kilowatt
kWh	Kilowatt-hours
l	Litre
LCOeA	Levelized cost of eAmmonia
LCOeEl	Levelized cost of electricity
LCOeF	Levelized cost of eFuel
LCOeH	Levelized cost of eHydrogen
LCOF	Levelized cost of fuel
LCOT	Levelized cost of transport
LCOTA	Levelized cost of transport aviation
LCOTS	Levelized cost of transport shipping
LCOTT	Levelized cost of transport trucking
LCOX	Levelized cost of an arbitrary process
LH_2	Liquid hydrogen
LHV	Low heating value
m	Meters
M	Million
m^3	Cubic metre
MTOW	Maximum take of weight
N	Lifetime
N_2	Nitrogen
O&M	Operation and maintenance
Opex	Operational expenditures
PEM	Polymer electrolyte membrane
Q	Annual outcome quantity
R&M	Repair and maintenance
SHF	Sustainable hydrogen fuels
SI	Supplementary information
t	Tonnes
TLCC	Total lifecycle cost
TCO	Total cost of ownership
TEU	Twenty-foot equivalent unit
UCRF	Universal capital recovery factor
ULRC	Underground lined rock cavern
var	Variable
WACC	Weighted average cost of capital

Data for fuel and transport cost calculations

We collect raw data for 140 parameters throughout the value chains in five-year increments from 2020 to 2050 based on publicly available data from articles in peer-reviewed scientific journals and frequently cited reports by consultants, agencies and industry experts, validated by practitioners. We interpolate missing data for specific years as needed. If more than one or no reference is listed in Table **1**, we build a weighted average based on our interviews with experts and our own expertise. Following the literature, we assume all costs at industrial scale and increasing market diffusion. Hence, strong scaling and learning effects for all components shape the cost curves. The upper and lower bounds in parentheses represent the uncertainties used in the sensitivity analysis. Data on energy content always refer to the low heating value (LHV). Table 1 is an extract for 2020, 2035 and 2050.

Table 1: Extract of data for 2020, 2035 and 2050. The upper and lower bounds in parentheses represent the uncertainties used in the sensitivity analysis. Data on energy content always refer to the low heating value (LHV).

	2020	**2035**	**2050**
Offshore wind			
Capex [€/kW$_{el}$]	3,200 (+/-500)[1–5]	2,000 (+495/-505)[1–4]	1,650 (+/-500)[1–4]
Opex [% of Capex]	3[2,5]		
Lifetime [a]	25[2,5]		
Full load hours [h/a]	4,400 (+/-100)[5–7]		
Sea cable [ct/kWh]	1.50[2]	1.04[2]	0.70[2]
Onshore wind			
Capex [€/kW$_{el}$]	1,500 (+/-150)[1,2,5,8,9]	1,030 (+305/-295)[1,2,4,9]	950 (+/-250)[1,2,4,9]
Opex [% of Capex]	2.5[1,2,5,9]		
Lifetime [a]	20[1,2,5,9]		
Full load hours [h/a]	3,200 (+/-200)[2,5,7]		
Large hydro			
Capex [€/kW$_{el}$]	2,350[2,10]		
Opex [% of Capex]	2.5[2,10]		
Lifetime [a]	50[2,10]		
Full load hours [h/a]	7,000 (+/-1,000)[2,10,11]		
CO_2 direct air capture			
CO_2 [€/t]	460 (+/-90)[2,12–14]	135 (+/-42)[2,12,14]	80 (+/-30)[2,12,14]
Electrolyser (PEM/ALK)			
Capex [€/kW$_{el}$]	1,100 (+/-390)[2,12,15,16]	525 (+235/-230)[2,12,15,16]	330 (+/-190)[2,12,15,16]
Opex [% of Capex]	3[2,9,17]		
Lifetime [a]	25[2,9,16]		
Full load hours [h/a]	Equal to electricity source		
Efficiency [%]	64.2 (+/-5.7)[12]	67 (+/-7.0)[12]	72.2 (+/-6.9)[12]
Water cost	neglected		
H_2 buffer storage			
H_2 ULRC [ct/kWh$_{H2}$]	0.98[18]		
Storage need [% of total H_2]	100		
eFuel synthesis			
Capex [€/kW$_{fuel}$]	800 (+/-150)[2,12,19]	525 (+260/-125)[2,12,19]	400 (+300/-100)[2,12,19]
Opex [% of Capex]	3.5[2,19]		
Lifetime [a]	25[2,19]		
Full load hours [h/a]	8,000[2]		
Feedstock H_2 [kWh$_{H2}$/kWh$_{fuel}$]	1.25[2]		
Feedstock CO_2 [kg$_{CO2}$/kWh$_{fuel}$]	0.341[2,20]		

Feedstock electricity [kWh_{el}/kWh_{fuel}]	0.045[20]		
eAmmonia synthesis			
Capex [€/kW_{fuel}]	995 (+/-50)[9]		
Opex [% of Capex]	5[9]		
Lifetime [a]	30[9]		
Full load hours [h/a]	8,000[9]		
Efficiency [%]	99[9]		
Feedstock electricity [kWh_{el}/t_{fuel}]	738[9]		
Feedstock H_2 [kg_{H2}/t_{fuel}]	177[21]		
Feedstock N_2 [kg_{N2}/t_{fuel}]	823[21]		
H_2 liquefaction			
Capex [€/kW_{H2}]	2,300[22]	1,255 (+0/-255)[21,22]	700 (+300/-0)[22]
Opex [% of Capex]	2[20]		
Lifetime [a]	30[22]		
Full load hours [h/a]	8,000[22]		
Feedstock electricity [kWh_{el}/kWh_{H2}]	0.360[21,22]	0.222[21,22]	0.210[21,22]
H_2 evaporation [%]	5[20]		
Tank semi-trailer			
LH_2 - Capex [€/trailer]	750,000[20,23]	380,000[20,23,24]	250,000[20,23,24]
LH_2 - Net capacity [kg]	4,300[23,25]		
LH_2 - Payload [kg]	4,500[23]		
fFuel/eFuel - Capex [€/trailer]	60,000[26]		
fFuel/eFuel - Net capacity [m^3]	50		
Fuel independent			
Opex fix [% of Capex]	2[23]		
Mileage [km/a]	65,000[20,23]		
Lifetime [a]	12[23]		
Trip length [km]	150		
Return trip	empty		
Truck unit			
Capex [€/truck unit]	90,000[20,23,26]		
Opex fix [% of Capex]	10[23,26]		
Opex var incl. trailer [€/km]	0.125[20,26]		
Mileage [km/a]	65,000[20,23]		
Lifetime [a]	9[20,23]		
Fuel demand [kWh/km]	3.2 (32 l/100km)[23,27]		
Average speed [km/h]	50		
Driver salary incl. social security [€/h]	25		
Working days; hours [days/a, h/day]	230; 8		
Diesel price net at fuel station [€/l]	1[26]		
Fuel shipping			
LH_2 tank ship [ct/kWh*100km]	0.045[12]	0.039[12]	0.038[12]
eFuel tank ship [ct/kWh*100km]	0.0075[12]	0.0043[12]	0.0025[12]
eAmmonia tank ship [ct/kWh*100km]	0.0125[12]	0.0093[12]	0.0075[12]
Distance shipped [km]	500		
Fuel buffer (liquid)			
eH [ct/kWh]	3[23]	1.67	1[21,24]
eF [ct/kWh]	0.04[21]		
eA [ct/kWh]	0.325[21]		
Fuel station (truck)			
fFuel/eFuel - Capex [M€/station]	2		
eH - Capex [M€/station]	6[20,28,29]	4[20,29]	3
eH - Fuel station utilisation rate [%]	70	85	100
Fuel independent			
Opex [% of Capex]	1.5[20,29]		
Fuel output max [GWh/a]	43[28]		
Lifetime [a]	15[29]		
Long-haul trucking			
Cargo trailer			
Capex trailer [€]	40,000[26]		

Lifetime [a]	12[23]		
Max. payload [t]	25[27]		
Occupancy rate [%]	100		
Truck (fuel independent)			
Mileage [km/a]	120,000[20,26,27]		
Lifetime [a]	10[20,23]		
R&M, tyres incl. trailer [€/a]	15,000[20,23,26,29]		
Insurance, fees incl. trailer [% of Capex]	5[26]		
General expense (office) [€/a]	3,000[26]		
Driver salary incl. social security [€/a]	60,000		
Working days; hours [days/a, h/day]	245[26]; 8		
Travel expense [€/a]	7,000		
Road tolls Norway [€/km]	0.11[30]		
Truck (fuel dependent)			
fFuel/eFuel (internal combustion engine)			
Capex [€/truck unit]	110,000[23,26,29]		
Fuel demand [kWh_{LHV}/km]	3.2 (32l/100km)[23,26,29]		
eHydrogen (fuel cell)			
Capex [€/truck unit]	350,000 (+50,000/-50,0000)[26,27,29,31]	150,000 (+50,000/-20,000)[29,32]	140,000 (+20,000/-40,000)[29,32]
Fuel demand [kWh/km]	2.98 (+/-0.161)[12,29,33,34]	2.75 (+/-0.161)[12,29,33,34]	2.69 (+/-0.161)[12,29,33,34]
Short-haul aviation			
Aviation (fuel independent)			
MTOW [t]	73.5[35]		
Max. payload [t]	20[36]		
Flight control rate [€/Bh]	444[37]		
Fuel handling cost airport [ct/kWh]	0.15		
Crew [€/Bh]	500[38,39]		
Maintenance variable [€/Bh]	501[37]		
Maintenance fixed [€/Bh]	401[39]		
Insurance aircraft [% of Capex]	1.35[39]		
Cargo handling [€/flight]	150[37]		
Ground handling [€/flight]	1,379[37]		
Airport fee [€/flight]	649[37]		
Block hours per year [Bh/a]	3,300[37]		
Lifetime [a]	25		
Aviation (fuel dependent)			
fFuel/eFuel (jet engine)			
Capex aircraft [M€]	50[40]		
Occupancy rate [%]	100%		
Fuel demand [kWh/km]	38.8 (4 l/km)[27,35]		
eHydrogen (jet engine)			
Capex aircraft [M€]		125 (+/-25)[40,41 42]	65 (+35/-10)[40,41]
Occupancy rate [%]		75[27,41–43]	75[27,41–43]
Fuel demand [kWh/km]		38.8[41]	38.8[41]
Short-sea shipping			
Shipping (fuel independent)			
Mileage [km/a]	152,011[44,45]		
Average days at sea [days]	190[45]		
Working days [days/a]	240		
Loading and unloading days [days/a]	50		
Ship length [m]	135[44]		
Installed power [kW]	7,200[44]		
Service speed [knots]	18[44]		
Lifetime [a]	25[46]		
Insurance [% of Capex]	2[47]		
Maintenance [€/a]	775,000[47]		
Crew salary incl. social security [€/h]	200		
Travel expense [€/a]	25,000		
General expense [€/a]	50,000[47]		
Max. payload (dead-weight) [t]	9,450[44]		

Max. container (20Ft) [TEU]	750[44]		
Occupancy rate [%]	100		
Port fee [€/container]	45[48]		
Shipping (fuel dependent)			
fFuel/eFuel (internal combustion engine)			
Capex ship [M€/ship]	50[46,47]		
Tank capacity HFO [GWh]	9[44]		
Fuel demand [kWh/km]	498 (35t/24h)[44]		
Lubrication [€/a]	350,000[44,47]		
eHydrogen (fuel cell)			
Capex ship [M€/ship]		100 (+20/-17.5)[46,49]	65 (+10/-5)[46,49]
Fuel demand [kWh/km]		411 (+/-24.9)[33]	400 (+/-24.9)[33]
Lubrication [€/a]		0	0
eAmmonia (fuel cell)			
Capex ship [M€/ship]		100 (+20/-17.5)[46]	60 (+10/-5)[50]
Fuel demand [kWh/km]		411 (+/-24.9)[33]	400 (+/-24.9)[33]
Lubrication [€/a]		0	0
Auxiliary data			
WACC	6 %		
Energy density (LHV)			
Diesel	11.89 kWh/kg, 10 kWh/l, 0.841 kg/l[51]		
HFO	11.39 kWh/kg, 11.28 kWh/l 0.99 kg/l[27,51]		
Jet fuel A-1	11.99 kWh/kg, 9.7 kWh/l, 0.809 kg/l[27,51]		
eHydrogen	2.359 kWh/l_{liquid}, 3.00 kWh/Nm^3, 33.33 kWh/kg[52,53]		
eAmmonia	5.28 kWh/kg, 3.19 kWh/l_{liquid}, 0.604 kg/l[27,53]		
eFuel (simplification; see auxiliary data)	11.50 kWh/kg, 10.00 kWh/l[27,51], 0.87 kg/l		
External energy purchase			
Grid electricity prices, contract for services excl. taxes [€/kWh_{el}]	0.031(+/-0.014)[54]		
Grid electricity prices, contract for energy-intensive manufacturing excl. taxes [€/kWh_{el}]	0.0275 (+/-0.0045)[55]		
Diesel prices (stock exchange), excl. taxes [€/l]	0.70 (+/-0.28)[56]		
Jet fuel A-1 prices (stock exchange), excl. taxes [€/l]	0.40 (+0.14/- 0.19)[57]		
HFO (IFO380) prices (stock exchange), excl. taxes [€/t]	0.36 (+0.1/-0.16)[58]		
NOK/€	10		
USD/€	0.85		

Renewable electricity generation

Offshore wind

For wind installation off Norway's coast, we assume a moderate complexity on the mid- to lower-bound of existing cost estimations including uncertainty as the cost range[1–3,5]. Our Capex degradation is in line with Wiser et al. (2021)[4], an expert elicitation survey defining a degradation potential of -35% for 2030 and -49% for 2050. Opex as 3% of Capex and a lifetime of 25 years are close to or in line with the literature[2,5]. We use full load hours for Sørlige Nordsjø II[6], validated by Staffell and Pfenninger (2016)[7] and Kost et al. (2021)[5]. We include additional costs for the undersea connection to the mainland following Deutsch et al. (2018)[2].

Onshore wind

For wind installation in Norway, we assume a medium complexity on the mid-bound of existing cost estimations including uncertainty as the cost range[1,2,5,8,9]. Our Capex degradation is in line with Wiser et al. (2021)[4], an expert elicitation survey defining a degradation potential of -27% for 2030 and -37% for 2050. Opex as 2.5 % of Capex and a lifetime of 20 years are close to or in line with the literature[1,2,5,9]. We use full load hours for a coastal wind location[2,5] near Stavanger, validated by Staffel and Pfenninger (2016)[7]and Kost et al. (2021)[5].

Large hydro

For a large hydro installation in Norway's interior, we assume 290 MW electric power and apply a constant Capex over the time period without further reduction potential[2,10]. Opex as 2.5%[2,10] of Capex and a lifetime of 50 years are close to or in line with the literature[2,10]. We use full load hours for "Aura"[11] in Mid-Norway, which generates electricity for continuous industrial alumina production. The best-case scenario considers the ability to offer baseload electricity. The worst-case scenario is just below the local production of 6,400 hours per year[11].

CO_2 direct air capture

For a direct air capture installation in Norway based on low-temperature solid sorbent technology, we follow market leader Climeworks[13]. Since the technology is still a prototype, and cost data are limited and forecasts are widely spread[2,12,14,59], we first assumed 460 €/t CO_2[12] for 2020 which is slightly lower than $600 per tonne CO_2 from Climeworks in 2017[13]. After consulting with our industry experts, we now assume 135 €/t CO_2 in 2035 and 80 €/t CO_2 in 2050, which are averages in the literature[2,12,14].

Electrolysis

For a large electrolysis installation in Norway, we follow the latest cost review of Ueckerdt et al. (2021)[12], including uncertainty as the cost range[12,15,19]. Alkaline and proton exchange membrane electrolysers are commercially available and are suitable for the energy transition[16]. We assume an average value for both technologies representing the electrolysers. We assume an increase in electrolyser efficiency[12], common Opex and lifetime following the literature[2,9,16,17]. We harmonize full load hours of hydrogen production with the renewable energy source chosen. We calculate water costs per kilowatt hour hydrogen, but neglect them due to insignificance.

H_2 buffer storage

All further process steps such as hydrogen liquification and fuel synthesis require a constant mass flow of hydrogen[9,19,22], so we include H_2 underground lined rock caverns (ULRC) as buffer storage for compressed hydrogen[60]. We assume a levelized storage cost of 0.98 ct/kWh[18] hydrogen and apply it to the entire production volume.

eFuel synthesis

Hydrocarbon synthesis requires continuous production with high full load hours per year[2,19]. The renewable electricity needed comes from the grid with a standard price for energy-intensive manufacturing excluding taxes[55]. For simplicity, we apply data representing Fischer-Tropsch synthesis and methanol synthesis technologies, which is in line with the literature[2,12,19,21]. We assume Capex values following the literature review of Brynolf et al. (2018)[19], and include uncertainty as the cost range[2,12,21]. The exact share of hydrogen, carbon and electricity as feedstock depends on the end-product, so we calculate eFuel based on the average values from the literature[2,20].

eAmmonia synthesis

eAmmonia synthesis requires continuous production with high full load hours per year[9]. The renewable electricity needed comes from the grid with a standard price for energy-intensive manufacturing excluding taxes[55]. We assume Capex values following Fasihi et. al. (2021)[9] and convert them into euros per kilowatt of ammonia, and offset the investment cost for ammonia liquefaction (-33 °C[61]) in the plant Capex[9]. The underlying Haber-Bosch process used in fertilizer production is a sophisticated technology, so we neglect further cost reduction[9].

H_2 liquefaction

H_2 liquefaction requires continuous production with high full load hours per year, cooling the gas down to -253 °C and forcing it to change into a liquid state (LH_2)[22]. The renewable electricity needed comes from the grid with a standard price for energy-intensive manufacturing excluding taxes[55]. We assume electricity demand following Hank, Sternberg et al. (2020)[21] as a starting value in 2020 and build an average between them and Cardella et al. (2017)[62] for 2040. For Capex, we reduce the cost estimate for "today" of 2,800 €/kW_{el} in Brinner et al. (2018)[22] (originally based on year 2009) to 2,300 €/kW_{el}. For 2040, we expect their long-term cost target[22], which is also in line with the reduction potential of 2/3 for large-scale plants calculated by Cardella et al. (2017)[62]. For both electricity demand and Capex, we assume that the target values are reached in 2040 and stable thereafter. We assume a hydrogen evaporation rate of 5%[20].

Fuel shipping

The literature rarely mentions the costs for LH_2-tank ships[21] because large-scale prototypes exist only as concepts. Compared to existing tank ships for ammonia and crude oil, the limited amount per shipment and insulation requirements for liquid hydrogen significantly add to the distribution costs[12,21]. For all fuel types, we calculate a cost for shipping over 4,000 km as the order of magnitude, following Ueckerdt et al. (2021)[12], and assume a linear relation to translate it into specific costs in €/100*km. We assume an average distance of 500 km to supply a majority of Norwegian ports and airports.

Fuel buffer (liquid)

After shipping fuel to the nearest port of consumption, we assume a buffer storage to balance mismatched tank truck refilling. In case of direct bunkering between tank ships and end-use ships, we consider the storage as buffer between production and tank ship refilling. For eH we use existing data for liquid hydrogen storage following Reuß et al. (2017)[23] and NASA (6,6 M Dollar for 3,500 m^3 tank[24]). We assume NASA's long-term cost reduction target of 50%[21,24] for 2045. For eA and eF buffers we consider no further cost reductions over time due to mature technology following Hank et al. (2021)[21].

Tank semi-trailer and truck unit

We assume that tank semi-trucks, with truck unit and separate tank semi-trailer, supply inland fuel stations, which is a cost-efficient solution for countries where pipeline distribution has techno-economic limits[63]. Due to insulation needs, Capex for LH_2 trailers are higher than for common fuel trailers[20,23,25], but we assume a 33% cost reduction for liquid tanks until 2050[24] and neglect boil-off effects. For eF and fF, we assume a common diesel trailer without further need for conditioning[23]. Based on our market analysis, we assume trailers with a net fuel capacity of 50 m^3 which are empty on return trips.

For the truck unit, we apply common market values for Capex and Opex[20,23,26]. For simplicity, we assume diesel-fuelled trucks from 2020 to 2050. We assume a net diesel price of 1€ per litre at fuel stations, and neglect Norway's taxes of about +100%. We assume common values for mileage, lifetime, average speed and working days per year, which is in line with the literature[20,23,26,27]. We assume an average distance of 150 km distribution between the nearest port and inland fuel stations.

Fuel station (truck)

Fuel station operations run on renewable grid electricity with a standard price for the service sector excluding taxes[54]. For simplicity, we assume an existing eHydrogen fuel station network consisting of stations having liquid hydrogen storage and four truck fuel nozzles offering compressed hydrogen on a pressure of 700 bar[28]. With a yearly output of 43 GWh hydrogen, each fuel station supplies more than 50 heavy-duty trucks per working day, assuming fully depleted fuel tanks (tank capacity 80 kg hydrogen)[28,29]. We calculate and allocate the levelized cost of a representative heavy-duty fuel station per fuel dispensed based on interviews with our experts and other sources[20,28,29]. For an fFuel station serving long-haul transport, we assume a constant Capex of 2 M€ from 2020 to 2050, which also applies to the eFuel case. For an eHydrogen fuel station we calculate with factor 3[20,28,29] in 2020, 2[20,29] in 2035 and 1.5 in 2050, proportionally. For eHydrogen, we also include a utilization rate, considering early weaker fuel demand due to a shortage of fuel cell trucks.

Long-haul trucking

We assume a common 40-tonne semi-truck with truck unit and separate cargo semi-trailer[23,26,29]. All costs characterizing the truck body and trailer are identical[23,26,29]. We assume an identical vehicle for the benchmark fFuel (truck diesel) and the alternative eFuel. We assume the truck unit has a fuel-cell driven electric motor and a hydrogen tank for compressed eHydrogen (700 bar). We consider costs of necessary replacements of components, such as fuel cells, over the vehicle's lifetime by assuming proportionally higher CAPEX. For eHydrogen we apply a factor of 3.2[26,27,29,31] in 2020, 1.4[29,32] in 2035 and 1.3[29,32] in 2050, proportionally to the Capex of a fossil-fuel–based truck[23,26]. See Table **1** for the cost range of Capex. We depreciate all vehicles over their lifetime to circumvent the uncertainty of residual values for new technologies. Calculating the fuel efficiency, we assign 32 l diesel per 100 km[23,26,29] to an efficiency of 38%[27]. The fuel cell-based drive train has a total efficiency of 45.0% in 2020 (60%[29,33] fuel cell, 75%[12] el. engine and battery), 52.1% in 2035 (69,4%[33] fuel cell, 75%[12] el. engine and battery) and 54.0% in 2050 (72%[33] fuel cell, 75%[12] el. engine and battery), proportionally. See Table **1** for the efficiency range applying +/- 5% variation as uncertainty. We assume that combustion engine research eventually ceases and neglect further efficiency gains. For maintenance cost, we assume a compensation of low-maintenance electric drive trains and less optimized services. We assume the same maintenance cost for all fuel types. To determine the total cost of ownership, we use market data from interviews with our experts and other sources[20,23,26,27,29,33,64].

Road tolls vary throughout Norway, so we calculate an average value for the transport triangle Oslo-Bergen-Trondheim (with AutoPass, diesel truck, >3.5 tonnes, Euro VI)[30], to represent the costs of the road infrastructure used. Although Norway's toll system excludes sustainable freight transport[30], we neglect government intervention.

Short-sea shipping

Short-sea shipping denotes maritime freight transport along coastlines between countries on the same continent. We use the publicly available data on Enforcer[44], a typical mid-sized container ship[45]. For all fuel types, we assume the same occupancy rate and neglect any loss of cargo hold caused by different fuel energy densities, assuming adjustments in future ship design. For a vessel using fFuel (heavy fuel oil, HFO) or eFuel, we use Capex of 50 M€[44,46]. We assume ~5 M€ for the internal combustion engine (7.200 kW) with HFO tank (9 GWh), following Horvath et al. (2018)[49] and Hansson et al. (2020)[50]. For the eHydrogen ship (fuel cells and cryotanks), we use the long-term values of Taljegard et al. (2014)[46] and Horvath et al. (2018)[49], and assume a factor of 2 in 2035 and 1.3 in 2050, proportionally to the Capex of the fFuel case. For the eAmmonia case (fuel cells and cooling tanks), we assume a simpler on-board fuel storage[49,65] and initially higher fuel cell costs[49,53], and assume a factor of 2[46] in 2035 and 1.2[50] in 2050. We consider costs of necessary replacements of components, such as fuel cells, over the vehicle's lifetime by assuming proportionally higher CAPEX. See Table **1** for the cost range of Capex.

We assume a fuel demand of around 35 t/day[44] including auxiliary engine fuel and assign it to an engine efficiency of 45%[27,46,49,50]. Both fuel-cell–based drive trains have a total efficiency of 62,5% (69,4%[33] fuel cell, 90%[12] el. engine) in 2035 and 64,8% in 2050 (72%[33] fuel cell, 90%[12] el. engine), proportionally (market launch 2030[50]). See Table **1** for the efficiency range applying +/- 5% variation as uncertainty. We assume combustion engine research eventually ceases and neglect further efficiency gains for combustion engines.

For maintenance cost, we assume a compensation of low-maintenance electric drive trains and less optimized services. We assume the same maintenance cost for all fuel types.

To identify the total cost of ownership we collect market data from our expert interviews and other sources[44–47]. There are regional variations of port fees, so we calculate the cost of Enforcer[44] at Bergen port[48] with a fairway fee, quay fee, cargo fee, loading/unloading fee and administrative fee. Although Norway excludes sustainable freight transport from public fees, we neglect government intervention.

Short-haul aviation

We use the specifications of the Airbus A320[27,35,36,40] adjusted to the freighter version produced by Elbe-Flugzeug-Werke (A320-P2F)[36]. Although the freighter version is usually offered as a retrofit of second-hand passenger planes, we assume costs for new planes. The Airbus A320 list price of 110 M USD in 2018[40] is publicly available, but airlines commonly order many planes to take advantage of high discounts[39]. We assume Capex of 50 M€ for a new freighter with fFuel (Jet A-1) or eFuel. Cost estimates for eH-based planes are rare[41], so we use the recently published design of the Airbus Turbofan[42] with a planned market launch in 2035. The plane has hydrogen storage cryotanks in the rear and the fuel burns in modified turbine engines. For Capex, we choose a factor of 2.5 in 2035, expecting significantly higher costs in the market launch year compared to conventional planes[27]. For 2050 we assume a massive cost decrease to a factor of 1.3 that still meets the challenges of complex fuel storage technology[27,41]. See Table **1** for the cost range of Capex. Aircraft leasing is common, but we purchase and fully depreciate planes over their lifetimes, which leads to noticeably higher Capex costs compared to leasing values[39]. By using a constant methodology however, we obtain a better comparison to other transport modes. Assessing recent developments in aviation design[42], we assume an occupancy rate of 75%[27,41,43] for hydrogen-fuelled planes, which represents the expected loss of cargo hold due to the weight and volume of cryotanks[27]. We assume a compensation of the higher tank mass with the considered occupancy limit and assume the same fuel demand for all fuel types[41]. Although the current regulations only allow a blending of 50%[66] Fischer-Tropsch-based eF we assume a 100% fF substitution to achieve full decarbonization.

To identify the total cost of ownership we use a detailed cost breakdown for operating an A320 passenger flight with 1,350 km and 2.33 block hours following Brützel (2017)[37,39], adjusted and supplemented with freight-specific parameters[36] and data from interviews with our experts. We assume the same maintenance cost for all fuel types. Equal to existing refuelling, we assume direct bunkering between tank trucks and aircraft for all cases[67].

Auxiliary data

Weighted average cost of capital (WACC) significantly affects final costs, so we consider values for sustainable energy investments (3–5%[68]) and transport investments (10%[68]), following Short et al. (1995), and apply a value of 6% for all calculations.

For eFuel use, we simplify the calculations and do not distinguish between synthetic diesel, maritime fuel and jet fuel by using an average value (11.5 kWh/kg, 10 kWh/l) representing all subtypes. See Table **1** for the energy densities of the fuel types.

We use 2012–2021 data on Norwegian grid electricity prices for energy-intensive manufacturing[54,55] and services[54] excluding taxes and subsidies. We assume 100% renewable electricity from 2020 to 2050.

We compare eH, eA and eF fuels with their fF substitutes (trucking: diesel, shipping: HFO, aviation: Jet A-1). Considering fossil fuel price volatility, we include a range of historic values. For trucking, we use stock market prices for diesel between 2011 and 2021[56], for shipping, we use stock market prices for HFO between 2019 and 2021[58] and for aviation, we use stock market prices for Jet A-1 between 2014 and 2021[57]. We neglect all taxes and subsidies. We apply the same distribution costs of eFuel to the fFuel case. The error bars in Figures 2–7 (paper) show the effects of the cost variations for each fuel.

Sensitivity analysis

We use best- and worst-case scenarios to investigate data uncertainties for the future technologies. We calculate the maximum error distribution and add it as error bars to our results in Figures 2–7 (paper). We choose the 23 most uncertain parameters based on our internal data collection and also follow the literature on large data distribution.

The 23 most uncertain parameters are:

- Capex wind power (offshore/onshore)
- Full load hours wind power (offshore/onshore)
- Full load hours hydropower
- CO_2 cost direct air capture
- Capex electrolysis
- Efficiency electrolysis
- Capex eFuel synthesis
- Capex eAmmonia synthesis
- Capex hydrogen liquefaction
- Capex hydrogen truck

- Fuel demand hydrogen truck
- Capex hydrogen aircraft
- Capex hydrogen/ammonia vessel
- Fuel demand hydrogen/ammonia vessel
- Grid electricity stock prices (energy-intensive manufacturing/services)
- Diesel stock prices excl. taxes
- Jet fuel refinery prices excl. taxes
- HFO stock prices excl. taxes

References

1. IRENA. *Future of wind. Deployment, investment, technology, grid integration and socio-economic aspects* (Abu Dhabi, 2019).

2. Agora Verkehrswende, Agora Energiewende & Frontier Economics. *The future cost of electricity-based synthetic fuels* (frontier economics, Berlin, 2018).

3. Musial, W. *et al. Offshore wind market report. 2021 edition* (U.S. Department of Energy, Washington DC, 2021).

4. Wiser, R. *et al.* Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050. *Nature Energy* **6,** 555–565; 10.1038/s41560-021-00810-z (2021).

5. Kost, C. *et al. Levelized cost of electricity renewable energy technologies* (Fraunhofer Institute for Solar Energy Systems, Freiburg, 2021).

6. Norwegian Government. Opening of the areas Utsira Nord and Sørlige Nordsjø II for processing of applications for licences for renewable energy production pursuant to the offshore energy act. Case no: 20/88- (Unofficial translation). Available at https://www.regjeringen.no/contentassets/aaac5c76aec242f09112ffdceabd6c64/royal-decree-opening-of-areas-june-2020.pdf (2020).

7. Staffell, I. & Pfenninger, S. Using bias-corrected reanalysis to simulate current and future wind power output. *Energy* **114,** 1224–1239; 10.1016/j.energy.2016.08.068 (2016).

8. IRENA. *Renewable power generation costs in 2020* (IRENA, Abu Dhabi, 2021).

9. Fasihi, M., Weiss, R., Savolainen, J. & Breyer, C. Global potential of green ammonia based on hybrid PV-wind power plants. *Applied Energy* **294,** 116170; 10.1016/j.apenergy.2020.116170 (2021).

10. IRENA. *Hydropower. Renewable energy technologies: Analysis series* (IRENA, Bonn, 2012).

11. NVE. NVE Atlas - Data sheet Aura hydropower. Available at https://www.nve.no/energi/energisystem/vannkraft/vannkraftdatabase/vannkraftverk/?id=9 (2021).

12. Ueckerdt, F. *et al.* Potential and risks of hydrogen-based e-fuels in climate change mitigation. *Nature Climate Change* **11,** 384–393; 10.1038/s41558-021-01032-7 (2021).

13. Tollefson, J. Sucking carbon dioxide from air is cheaper than scientists thought. Available at https://www.nature.com/articles/d41586-018-05357-w (2018).

14. Fasihi, M., Efimova, O. & Breyer, C. Techno-economic assessment of CO2 direct air capture plants. *Journal of Cleaner Production* **224,** 957–980; 10.1016/j.jclepro.2019.03.086 (2019).

15. Glenk, G. & Reichelstein, S. Economics of converting renewable power to hydrogen. *Nature Energy* **4,** 216–222; 10.1038/s41560-019-0326-1 (2019).

16. Smolinka, T. *et al. Study IndWEDe – brief overview. Industrialisation of water electrolysis in Germany: Opportunities and challenges for sustainable hydrogen for transport, electricity and heat* (NOW, Berlin, 2018).

17. Fasihi, M. & Breyer, C. Baseload electricity and hydrogen supply based on hybrid PV-wind power plants. *Journal of Cleaner Production* **243,** 118466; 10.1016/j.jclepro.2019.118466 (2020).

18. Ahluwalia, R., Papadias, D., Peng, J. & Roh, H. System level analysis of hydrogen storage options. Available at https://www.hydrogen.energy.gov/pdfs/review19/st001_ahluwalia_2019_o.pdf (2019).

19. Brynolf, S., Taljegard, M., Grahn, M. & Hansson, J. Electrofuels for the transport sector. A review of production costs. *Renewable and Sustainable Energy Reviews* **81,** 1887–1905; 10.1016/j.rser.2017.05.288 (2018).

20. Zerta, M. *et al. Strombasierte Kraftstoffe für Brennstoffzellen in der Binnenschifffahrt* (NOW, München, 2019).

21. Hank, C. *et al.* Energy efficiency and economic assessment of imported energy carriers based on renewable electricity. *Sustainable Energy Fuels* **4,** 2256–2273; 10.1039/D0SE00067A (2020).

22. Brinner, A., Schmidt, M., Schwarz, S., Wagener, L. & Zuberbühler, U. *Technologiebericht 4.1 Power-to-gas (Wasserstoff). Technologien für die Energiewende. Teilbericht 2 an das Bundesministerium für Wirtschaft und Energie (BMWi)* (Wuppertal Institut; ISI; IZES, Wuppertal, 2018).

23. Reuß, M. *et al.* Seasonal storage and alternative carriers. A flexible hydrogen supply chain model. *Applied Energy* **200,** 290–302; 10.1016/j.apenergy.2017.05.050 (2017).

24. NCE. *Norwegian future value chains for liquid hydrogen* (NCE Maritime Clean Tech, Stord, 2016).

25. Decker, L. Liquid hydrogen distribution technology. HYPER Closing seminar. Available at https://www.sintef.no/globalassets/project/hyper/presentations-day-2/day2_1105_decker_liquid-hydrogen-distribution-technology_linde.pdf (2019).

26. Braun, M. Sieben Kandidaten ziehen Bilanz. Das Ergebnis des trans aktuell-Fehrenkötter-Tests birgt nach zweieinhalb Jahren manche Überraschung. *trans aktuell,* 1–7 (2016).

27. Gray, N., McDonagh, S., O'Shea, R., Smyth, B. & Murphy, J. D. Decarbonising ships, planes and trucks. An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. *Advances in Applied Energy* **1**; 10.1016/j.adapen.2021.100008 (2021).

28. H2Mobility. *Hydrogen refuelling for heavy duty vehicles. Overview* (H2 Mobility Deutschland, Berlin, 2021).

29. Transport & Environment. *How to decarbonise long-haul trucking in Germany. An analysis of available vehicle technologies and their associated costs.* (Brussel, 2021).

30. Fremtind Service. Toll calculator Norway. Available at https://fremtindservice.no/business/toll-calculator/ (2022).

31. Boer, E. den, Aarnink, S., Kleiner, F. & Pagenkopf, J. *Zero emissions trucks. An overview of state-of-the-art technologies and their potential* (CE Delft, 2013).

32. Stenning, J. *et al. Trucking into a Greener Future. The economic impact of decarbonizing goods vehicles in Europe* (Cambridge econometrics, Cambridge, 2018).

33. Cullen, D. A. *et al.* New roads and challenges for fuel cells in heavy-duty transportation. *Nature Energy* **6,** 462–474; 10.1038/s41560-021-00775-z (2021).

34. Cunanan, C. *et al.* A review of heavy-duty vehicle powertrain technologies. Diesel engine vehicles, battery electric vehicles, and hydrogen fuel cell electric vehicles. *Clean Technol.* **3,** 474–489; 10.3390/cleantechnol3020028 (2021).

35. EASA. Type-certificate data sheet for Airbus A318, A320, A321. Available at https://www.easa.europa.eu/downloads/16507/en (2022).

36. EFW. A320/A321P2F. The new Airbus narrowbody freighter family. Available at https://www.elbeflugzeugwerke.com/fileadmin/pdfs/efw-druck-brochure-A320-02-Screen.pdf (2021).

37. Brützel, C. *Was kostet eigentlich ein Flug? (2)* (airliners.de, Berlin, 2017).

38. Wilke, P., Schmid, K. & Gröning, S. *Branchenanalyse Luftverkehr. Entwicklung von Beschäftigung und Arbeitsbedingungen* (Hans-Böckler-Stiftung, Düsseldorf, 2016).

39. Brützel, C. *Was kostet eigentlich ein Flug? (3)* (airliners.de, Berlin, 2017).

40. AIRBUS. *Airbus aircraft average list prices* (Airbus Media Relations, Blagnac, France, 2018).

41. McKinsey & Company. *Hydrogen-powered aviation. A fact-based study of hydrogen technology, economics, and climate impact by 2050* (FCH 2 JU; Clean Sky 2 JU, Luxembourg, 2020).

42. AIRBUS. ZEROe. Towards the world's first zero-emission commercial aircraft. Available at https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe (2020).

43. Baroutaji, A., Wilberforce, T., Ramadan, M. & Olabi, A. G. Comprehensive investigation on hydrogen and fuel cell technology in the aviation and aerospace sectors. *Renewable and Sustainable Energy Reviews* **106,** 31–40; 10.1016/j.rser.2019.02.022 (2019).

44. Confeeder. Data - Enforcer, Encounter, Endeavor, Energizer, Ensemble, Endurance. Available at https://www.confeeder.com/wp-content/uploads/sites/9/2017/02/DATA-ENFORCER-ENCOUNTER-ENDEAVOR-ENERGIZER-ENSEMBLE-ENDURANCE.pdf.

45. IMO. *Fourth IMO greenhouse gas study 2020* (International Maritime Organization, London, 2021).

46. Taljegard, M., Brynolf, S., Grahn, M., Andersson, K. & Johnson, H. Cost-effective choices of marine fuels in a carbon-constrained world. Results from a global energy model. *Environmental science & technology* **48,** 12986–12993; 10.1021/es5018575 (2014).

47. Tzannatos, E., Papadimitriou, S. & Katsouli, A. The cost of modal shift. A short sea shipping service compared to its road alternative in Greece. *European Transport* (2014).

48. Bergen Havn. Price list for use of infrastructure and services in the port of Bergen. Available at https://bergenhavn.no/wp-content/uploads/2020/02/PRICELIST-2020_EN-002-1.pdf (2020).

49. Horvath, S., Fasihi, M. & Breyer, C. Techno-economic analysis of a decarbonized shipping sector. Technology suggestions for a fleet in 2030 and 2040. *Energy Conversion and Management* **164,** 230–241; 10.1016/j.enconman.2018.02.098 (2018).

50. Hansson, J., Brynolf, S., Fridell, E. & Lehtveer, M. The potential role of ammonia as marine fuel. Based on energy systems modeling and multi-criteria decision analysis. *Sustainability* **12,** 3265; 10.3390/su12083265 (2020).

51. Danish Energy Agency & Energinet. *Technology data renewable fuels.* 5th ed. (Copenhagen, 2021).

52. Linde. Rechnen Sie mit Wasserstoff. Die Datentabelle. Available at https://www.linde-gas.at/de/images/1007_rechnen_sie_mit_wasserstoff_v110_tcm550-169419.pdf (2013).

53. Lan, R. & Tao, S. Ammonia as a suitable fuel for fuel cells. *Frontiers in Energy Research* **2,** 1–4; 10.3389/fenrg.2014.00035 (2014).

54. SSB. 09364: Electricity prices in the end-user market, by type of contract, quarter and contents. Service, excluding taxes. Available at https://www.ssb.no/en/statbank/table/09364/tableViewLayout1/ (2021).

55. SSB. 09364: Electricity prices in the end-user market, by type of contract, quarter and contents. Energy intensive manufacturing, excluding taxes. Available at https://www.ssb.no/en/statbank/table/09364/tableViewLayout1/ (2021).

56. Boerse Franfurt. Diesel. Available at https://www.boerse-frankfurt.de/rohstoff/diesel (2022).

57. IATA. Jet fuel price monitor. Available at https://www.iata.org/en/publications/economics/fuel-monitor/ (2021).

58. Ship&Bunker. Rotterdam bunker prices. IFO380. Available at https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam#IFO380 (2021).

59. Breyer, C., Fasihi, M. & Aghahosseini, A. Carbon dioxide direct air capture for effective climate change mitigation based on renewable electricity. A new type of energy system sector coupling. *Mitig Adapt Strateg Glob Change* **25,** 43–65; 10.1007/s11027-019-9847-y (2020).

60. Andersson, J. & Grönkvist, S. Large-scale storage of hydrogen. *International Journal of Hydrogen Energy* **44,** 11901–11919; 10.1016/j.ijhydene.2019.03.063 (2019).

61. Heinemann, C. *et al. Die Bedeutung strombasierter Stoffe für den Klimaschutz in Deutschland* (Öko-Institut, Freiburg, 2019).

62. Cardella, U., Decker, L. & Klein, H. Economically viable large-scale hydrogen liquefaction. *IOP Conference Series: Materials Science and Engineering* **171,** 12013; 10.1088/1757-899X/171/1/012013 (2017).

63. Reuß, M., Grube, T., Robinius, M. & Stolten, D. A hydrogen supply chain with spatial resolution: Comparative analysis of infrastructure technologies in Germany. *Applied Energy* **247,** 438–453; 10.1016/j.apenergy.2019.04.064 (2019).

64. Noll, B., Del Val, S., Schmidt, T. S. & Steffen, B. Analyzing the competitiveness of low-carbon drive-technologies in road-freight. A total cost of ownership analysis in Europe. *Applied Energy* **306,** 118079; 10.1016/j.apenergy.2021.118079 (2022).

65. Cheliotis, M. *et al.* Review on the safe use of ammonia fuel cells in the maritime industry. *Energies* **14,** 3023; 10.3390/en14113023 (2021).

66. Battteiger, V. *et al. Power-to-liquids. A scalable and sustainable fuel supply perspective for aviation* (German Environment Agency, Dessau-Roßlau, 2022).

67. AIRBUS. The green hydrogen ecosystem for aviation, explained. Available at https://www.airbus.com/en/newsroom/news/2021-06-the-green-hydrogen-ecosystem-for-aviation-explained (2021).

68. Short, W., Packey, D. J. & Holt, T. *A manual for the economic evaluation of energy efficiency and renewable energy technologies* (National Renewable Energy Laboratory, Golden, 1995).

Contact.

MIT CEEPR Working Paper Series
is published by the MIT Center for Energy and Environmental Policy Research from submissions by affiliated researchers.
For inquiries and/or for permission to reproduce material in this working paper, please contact:

General inquiries: ceepr@mit.edu
Media inquiries: ceepr-media@mit.edu

MIT Center for Energy and
Environmental Policy Research

MIT Center for Energy and
Environmental Policy Research
Massachusetts Institute of Technology
77 Massachusetts Avenue, E19-411
Cambridge, MA 02139-4307
USA

ceepr.mit.edu

MASSACHUSETTS INSTITUTE OF TECHNOLOGY